2016-09

Achieving ship's mission flexibility through designing, printing and operating unmanned systems with additive manufacturing and delayed differentiation

Sin, Mong Lin

Monterey, California: Naval Postgraduate School

http://hdl.handle.net/10945/50484

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

ACHIEVING SHIP'S MISSION FLEXIBILITY THROUGH DESIGNING, PRINTING AND OPERATING UNMANNED SYSTEMS WITH ADDITIVE MANUFACTURING AND DELAYED DIFFERENTIATION

by
Mong Lin Sin

September 2016

Thesis Advisor: Ronald Giachetti
Second Reader: Christopher Adams

Approved for public release. Distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** September 2016	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE ACHIEVING SHIP'S MISSION FLEXIBILITY THROUGH DESIGNING, PRINTING AND OPERATING UNMANNED SYSTEMS WITH ADDITIVE MANUFACTURING AND DELAYED DIFFERENTIATION			**5. FUNDING NUMBERS**
6. AUTHOR(S) Mong Lin Sin			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The design, print and operate (DPO) concept of operations (CONOPS) is proposed in this thesis as a new means of equipping ships with the appropriate capabilities. A companion concept of delayed differentiation is also introduced. In coupling the two concepts, additive manufacturing of capabilities in-situ becomes a possibility through the equipping of operational units with three building blocks: additive manufacturing systems and their raw materials, commercial off-the-shelf items and field programmable gate arrays.

A concept of operations on uses of additive manufacturing was developed to illustrate the flexibility that the nexus of DPO CONOPS and delayed differentiation can engender. A tactical unmanned aerial vehicle (UAV) was used as an illustration to contextualize the concept of operations to enhance the littoral combat ship's survivability when operating in the littorals. Assessments were then made on the feasibility of DPO CONOPS for shipboard uses. A tactical UAV was used as it was assessed to be operationally relevant and significant. Analytical models that could be iterated to achieve the specific-to-mission requirements were developed to analyze and assess the implementation approach. The models focused on the UAV's reliability in fulfilling the mission as well as the build-time of the UAV.

14. SUBJECT TERMS design, print and operate, DPO, unmanned aerial vehicle, UAV, concept of operations, CONOPS			**15. NUMBER OF PAGES** 149
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500

Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

ACHIEVING SHIP'S MISSION FLEXIBILITY THROUGH DESIGNING, PRINTING AND OPERATING UNMANNED SYSTEMS WITH ADDITIVE MANUFACTURING AND DELAYED DIFFERENTIATION

Mong Lin Sin
Military Expert 6, Republic of Singapore Navy
B.Eng EEE (Hons), Adelaide University, 2003

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2016

Approved by: Ronald Giachetti. Ph.D.
Thesis Advisor

Christopher Adams
Second Reader

Ronald Giachetti, Ph.D.
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The design, print and operate (DPO) concept of operations (CONOPS) is proposed in this thesis as a new means of equipping ships with the appropriate capabilities. A companion concept of delayed differentiation is also introduced. In coupling the two concepts, additive manufacturing of capabilities in-situ becomes a possibility through the equipping of operational units with three building blocks: additive manufacturing systems and their raw materials, commercial off-the-shelf items and field programmable gate arrays.

A concept of operations on uses of additive manufacturing was developed to illustrate the flexibility that the nexus of DPO CONOPS and delayed differentiation can engender. A tactical unmanned aerial vehicle (UAV) was used as an illustration to contextualize the concept of operations to enhance the littoral combat ship's survivability when operating in the littorals. Assessments were then made on the feasibility of DPO CONOPS for shipboard uses. A tactical UAV was used as it was assessed to be operationally relevant and significant. Analytical models that could be iterated to achieve the specific-to-mission requirements were developed to analyze and assess the implementation approach. The models focused on the UAV's reliability in fulfilling the mission as well as the build-time of the UAV.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

I. INTRODUCTION 1
A. BACKGROUND 1
B. CHALLENGES FACED BY THE NAVY 1
C. PROPOSED WAY AHEAD 2
D. VALUES PROPOSITION 2
1. Value Proposition 1—Tactical and Operational Flexibility 3
2. Value Proposition 2—Just-In-Time Production and Rapid Equipping, Offering Strategic Flexibility 3
3. Value Proposition 3—Minimal Investment in Rapidly Evolving Systems 4
E. THESIS ORGANIZATION 5

II. UNMANNED SYSTEMS—THEIR PROJECTED USES AND A CANDIDATE FOR DPO USING ADDITIVE MANUFACTURING 7
A. SECTION 1: USES OF THE UAV AND THE CONCERNS SURROUNDING THOSE USES 7
1. Background 7
2. Current Uses 8
3. Projected Uses 8
4. Unmanned versus Manned Aircraft 11
5. Challenges of Using UAVs 11
B. SECTION 2—THE CASE FOR ADDITIVE MANUFACTURING OF UAVS 13
1. Envisioned State 14
2. Enabling Approach 17
C. SECTION 3—TYPES OF UAVS, THEIR CLASSIFICATION AND THEIR FUNCTIONAL HIERARCHY 17
1. Types of Airframe 18
2. Other UAV Considerations 23
3. Context Diagram and Functional Hierarchy of the UAV 25
D. SUMMARY 36

III. AVAILABLE TECHNIQUES TO REALIZE ADDITIVE MANUFACTURING OF UAVS 37
A. SECTION 1—ADDITIVE MANUFACTURING AS BUILDING BLOCKS FOR UAV STRUCTURES AND CONTROL SURFACES 38

1. Concept of Additive Manufacturing—Layer by Successive Layer....40
2. Generalized Process Chain for Additive Manufacturing....42
3. Additive Manufacturing Technologies....47
4. Additive Manufacturing Systems—Process and Materials....50
5. Types of Additive Manufacturing System....53
6. Assessment of Additive Manufacturing System for Shipboard Use....59
B. SECTION 2—COMMERCIAL-OFF-THE-SHELF AS BUILDING BLOCK FOR SPECIALIZED ELECTRONIC MODULES....60
C. SECTION 3—FIELD PROGRAMMABLE GATE ARRAYS AS BUILDING BLOCKS FOR UAV CONTROL ELECTRONICS....63
1. Options for Implementing UAV Control Electronics....64
2. Direct-Write....64
3. Application Specific Integrated Circuit....66
4. Field Programmable Gate Array....67
D. SUMMARY....70

IV. APPROACH TO DPO OF UNMANNED SYSTEMS TO ENHANCE SHIP'S MISSION FLEXIBILITY....73
A. CONOPS TO ENHANCE MISSION FLEXIBILITY FOR SHIP'S MISSION....73
B. FEASIBILITY OF APPROACH....74
C. OPERATIONALIZING DPO CONOPS FOR ADDITIVE MANUFACTURING OF UAVS FROM SHIP....78
1. Assumptions....78
2. Additive Manufacturing of UAV....79
3. UAV Parts to be Additively Printed....79
D. DPO OF UAV....79
1. Structure and Control Surfaces....79
2. UAV Components....80
3. UAV's Electronics, Sensors and Control Module....81
E. SUMMARY....81

V. EXPANDING CONCEPT OF OPERATIONS WITH DPO-ENABLED SHIPS....83
A. CONCEPT OF OPERATIONS—USE OF ADDITIVELY MANUFACTURED UAVS TO ENHANCE SHIP SURVIVABILITY....83
1. Potential LCS Area of Operation....83

2. Survivability Analysis 88
3. Addressing Susceptibility of LCS 91
4. CONOPS for Additively Manufactured UAV-Forward Surveillance Using Constellation of UAVs 93
B. SUMMARY 95

VI. ANALYSIS OF FEASIBILITY FOR IN-SITU MANUFACTURING OF UAVS 97
A. OPERATIONAL AND TECHNICAL FEASIBILITY OF RAPIDLY MANUFACTURING UAV ONBOARD SHIP 97
1. Operational Feasibility 97
2. Technical Feasibility 98
B. TIME REQUIRED TO ADDITIVELY MANUFACTURE THE UAV 98
C. CAPABILITIES NEEDED ONBOARD THE SHIP 105
D. COTS REQUIRED TO REALIZE RAPID MANUFACTURING OF UAV ONBOARD SHIP 106
E. OTHER CONSIDERATIONS: UAV RELIABILITY 106
F. SUMMARY 111

VII. CONCLUSION AND FUTURE WORK 113
A. FUTURE WORKS 114
1. Stable Manufacturing Platform 114
2. Types of Joints for the UAV to Enable Rapid Integration After Additive Manufacturing 115
3. Types of Materials and the Associated Material Properties to Provide the Levels of Performance for the Additively Manufactured UAV 115

LIST OF REFERENCES 117

INITIAL DISTRIBUTION LIST 123

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

Figure 1. Flight Path of Malaysia Airlines Flight MH370. Source: Wikimedia Commons (2014). 10

Figure 2. Use of UAV Onboard Republic of Singapore Navy Missile Corvette. Source: Chua (2014). 10

Figure 3. Tasks Undertaken by the Military Across the Peace-to-War Continuum....13

Figure 4. Fundamental Types of HTOL. Source: Austin (2010, 35). 20

Figure 5. Fundamental Types of VTOL. Source: Austin (2010, 37). 21

Figure 6. Fundamental Types of Hybrid. Source: Austin (2010, 40)....23

Figure 7. Relative Efficiency versus Speed Ranges of Aircraft Types. Source: Austin (2010, 22). 25

Figure 8. Context Diagram of UAV System. 26

Figure 9. Functional Hierarchy of the UAV System—UAV. 29

Figure 10. Functional Hierarchy of the UAV System—GCS. 33

Figure 11. Physical Architecture of the UAV and GCS....36

Figure 12. Ratchet Wrench Printed in the International Space Station. Source: Harbaugh (2015). 39

Figure 13. Conceptual Comparison of Subtractive and Additive Manufacturing. Source: GAO (2015, 6). 41

Figure 14. 3D Printer Using Cartesian Systems. Source: Evans (2012, 2). 42

Figure 15. Process Chain for Additive Manufacturing. Source: Chua, Leong, and Lim (2003, 26). 43

Figure 16. (Left) CAD Model, (Right) STL Format. Source: Gibson, Rosen and Stucker (2010, 23)....43

Figure 17. Software Interface with the 3D Printer. 44

Figure 18. Cartesian Coordinate Additive Manufacturing System Used at Naval Postgraduate School....45

Figure 19. Example of an Additively Manufactured Object. 46

Figure 20. Example of an Imperfect Print Job (with Stray Fiber). 47

Figure 21. Different Direct-Write Techniques. Source: Piqué and Chrisey (2002, 4). 65

Figure 22. Micro-UAV Using Direct-Write Technique. Source: Piqué and Chrisey (2002, 4). 66

Figure 23. Examples of FPGAs. Source: Hamblen et al. (2006, 47). 67

Figure 24. CAD Tool Design Flow for FPGAs. Source: Hamblen et al. (2006, 56). 68

Figure 25. Examples of Small Aircraft with Additively Manufactured Parts by Aurora Flight Sciences. Source: NAS (2014, 20). 75

Figure 26. Additively Manufactured Drone Tested at Sea. Source: Marks (2015). 76

Figure 27. Uses of 3D Printer on Aircraft Carrier USS *Harry S. Truman* (CVN 75). Source: Vergakis (2015). 76

Figure 28. The Additively Manufactured Parts of the Jet Engine. Source: Szondy (2015). 80

Figure 29. Singapore Strait—A Vital Shipping Passage for Many Countries. Source: Australian Government Department of Defence (2013, 13). 84

Figure 30. Snapshots of the Busy Singapore Strait. Source: Kemp (2014). 85

Figure 31. Possible Disguised Small Boat Threats in Traditional Fishing Areas. Adapted from Hand (2013). 86

Figure 32. Sampan as Possible Small Boat Platform to Launch RPG and IED Attacks. Source: Sailing Totem (2014). 87

Figure 33. Kill Chain for Small Boat Threat against LCS. Adapted from Ball (2003, 11). 90

Figure 34. Example of Small Boat Attacker (Red) Staging for Close-by Surprise Attack on LCS (Blue). Adapted from Google Maps (n.d.). 92

Figure 35. Possible CONOPS for Enhancing Ship Survivability in the Littorals—Constant Surveillance Zone Using a Constellation of UAVs. 94

Figure 36. Possible CONOPS for Enhancing Ship Survivability in the Littorals— Threat Investigation...94

Figure 37. Four Key Steps for the “Printing of UAV.”...99

Figure 38. Screenshot of the Input to the Analytical Model. 101

Figure 39. Output of the Analytical Model for the Assessment of the UAV Build Time. 103

Figure 40. Screen Shot of the User Interface for Assessing Reliability of the Additively Manufactured UAV. 109

Figure 41. Comparison of Limiting Factors on the Reliability of the UAV. 110

Figure 42. Reliability of the UAV (with Improvement Factor Applied). 111

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

Table 1. Types of UAV. Adapted from Gupta, Ghonge, and Jawandhiya (2013, 1647). 17

Table 2. Classification of UAVs. Adapted from Gupta et al. (2013, 1652–1653). 18

Table 3. Three Broad Categories of Possible UAV Airframe Configurations. Source: Austin (2010, 34). 19

Table 4. Summary of Differences in HTOL Configurations. Adapted from Austin (2010, 35–36). 20

Table 5. Summary of Differences in VTOL Configurations. Adapted from Austin (2010, 37–38). 22

Table 6. Summary of Differences in Hybrid Configurations. Adapted from Austin (2010, 42) 23

Table 7. Functional Description of the UAV. 30

Table 8. Functional Description of the GCS. 33

Table 9. Enabling Approach for Implementation of the UAV System. 37

Table 10. Additive Manufacturing Technologies. 48

Table 11. Post-Processing Tasks for Different Additive Manufacturing Approaches. Adapted from Chua et al. (2003, 59). 49

Table 12. Types of Additive Manufacturing Processes. Adapted from GAO (2015, 6), Thomas and Gilbert (2014, 5). 50

Table 13. Additive Manufacturing Process and Material Combinations. Source: Wohlers (2012). 51

Table 14. Examples Of The Latest 3D Printers Introduced In 2015/6. 52

Table 15. Energy Consumption Of Five Additive Manufacturing Materials. Source: NAS (2014, 46). 55

Table 16. Comparison of Polyjet’s Additive Manufacturing System. Source: 3DPrintersCanada (2011b). 57

Table 17. Comparison of FDM Printer. Source: 3DPrintersCanada (2011b). 58

Table 18. Specialized Electronics Modules—Implementation Using COTS. 61

Table 19. Possible Components for the Make-up of an Additively Manufactured UAV. 77

Table 20. Survivability Enhancement Concepts. 89

Table 21. Notional Input to the UAV Build Process. 102

LIST OF ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
A_o	availability
A2/AD	anti-access/anti-denial
AEW	airborne early warning
AGL	above ground level
ALU	arithmetic logic unit
AM	additive manufacturing
ASIC	application specific integrated circuits
ATW	anti-tank weapons
AUM	all-up-mass
BLOS	beyond line of sight
BPM	ballistic particle manufacturing
C2	command and control
CAD	computer aided design
CAM	computer aided manufacturing
CCD	coherent change detection
CDMA	code division multiple access
CIC	combat information center
CLZ	craft-landing zone
CO2	carbon dioxide
COI	critical operational issues
COTS	commercial-off-the-shelf
CONOPS	concept of operations
CPLD	complex programmable logic arrays
CVD	chemical vapor deposition
DLMM	direct laser metal melting
DMP	direct metal printing
DOD	Department of Defense
DPI	dots per inch

DPO	design, print and operate
DR	data requirement
EBM	electron beam melting
EFFBD	enhanced functional flow block diagram
EO/IR	electro-optic/infra-red
EOD	explosive ordnance disposal
ESA	European Space Agency
EW	electronic warfare
FAA	Federal Aviation Authority
FDM	fused deposition method
FMECA	failure mode, effects, and criticality analysis
FPGA	field programmable gate array
FRT	failure rate
FTA	fault tree analysis
GCS	ground control station
GDP	gross domestic product
G-LOC	gravitational induced loss of consciousness
GPS	global positioning system
HADR	humanitarian and disaster relief
HALE	high altitude long endurance
HDL	hardware description language
HTOL	horizontal take-off and landing
IED	improvised explosive device
INS	inertial navigation system
ISR	intelligence, surveillance and reconnaissance
ISS	international space station
JIPB	joint intelligence preparation of battlespace
JIT	just in time
JMAP	joint military appreciation process
KSA	knowledge, skills and abilities
LCS	littoral combat ship
LE	logic elements

LOM	layered object manufacturing
LOS	line of sight
LPD	landing platform dock
LSI	large scale integration
NAS	national airspace
NASA	National Aeronautics and Space Administration
NOTAM	notice to aviators and mariners
NPS	Naval Postgraduate School
NVD	night vision device
MALE	medium altitude long endurance
MIL-SPEC	military specifications
MoE	measures of effectiveness
MoP	measures of performance
MSI	medium scale integration
MTBF	mean time between failures
MTI	moving target indicator
O&S	operation and support
OODA	observe, orientate, decide and act
OOTW	operations other than war
ROE	rules of engagement
ROV	remotely operated vehicle
RPG	rocket propelled grenades
RSN	Republic of Singapore Navy
RTK	real time kinematic
SAA	sense and avoid
SAMMS	self-propelled acoustic and magnetic mine sweeper
SAL	search and locate
SAR	search and rescue
SCS	solid creation system
SEAD	suppression of enemy's air defense
SGC	solid ground curing
SLA	stereo-lithography apparatus

SLOC	sea lines of communication
SLS	selective laser sintering
SLP	solid laser plotter
SOUP	solid object ultraviolet plotter
STL	stereo-lithography
T&E	tests and evaluations
TCO	total cost of ownership
TF	task force
TG	task group
TTP	tactics, techniques and procedures
TPM	technical performance measures
TUAV	tactical unmanned aerial vehicle
UAV	unmanned aerial vehicle
UCAV	unmanned combat aerial vehicle
UR	utilization rate
U.S.	United States
UV	ultra-violet
VHDL	VHSIC hardware description language
VHSIC	very high speed integrated circuit
VLSI	very large scale integration
VTOL	vertical take-off and landing

EXECUTIVE SUMMARY

Militaries have gone to war with what they have, not what they wished to have. This may no longer be the case in the future. This thesis evaluates the potential of the on-site and on-demand additive manufacturing of unmanned systems components. In exploiting the advancements made with the use of additive manufacturing techniques coupled with commercial off the shelf (COTS) technologies, it is possible to develop unmanned systems while a ship is deployed. The concept is predicated on the proposed three key processes of design, print and operate (DPO) to enable remote design of the unmanned systems by the domain engineer, the transmission of the design to a remote unit (e.g., ship) for printing using additive manufacturing, and finally operating it. Additive manufacturing systems, COTS, and field programmable gate arrays (FPGA) enable the DPO concept of operations (CONOPS).

Unmanned systems have garnered huge interest in the military to gain both tactical and strategic advantages while reducing the associated tactical and operational risks related to current manned practices. Specifically, a tactical unmanned aerial vehicle (UAV) of the Scan Eagle type is discussed, given that the tactical UAV is assessed to be operationally relevant and significant.

The thesis discusses the opportunities that could be reaped from the DPO concept, the possible CONOPS, and the benefits to the Navy at both the tactical and operational levels. The discussion covers the results and findings from the thesis on the feasibility of the DPO CONOPS to achieve ship's mission flexibility. Specific focus was on the use of DPO CONOPS for the in-situ manufacturing of UAVs to enhance the LCS's survivability when it is operating in the littorals. It is assessed that the in-situ manufacturing of UAVs is both technically and operationally feasible. It requires less than 24 hours to "print" a UAV in-situ with the additive manufacturing approach coupled with the use of COTS items to implement the common UAV functions and the use of a field programmable gate array to implement the command module for the UAV. The data and the analysis conducted demonstrated a near-term possibility of in-situ manufacturing of UAVs.

Through the work done in the thesis, the additive manufacturing approach was found to be a matured technology to use when coupled with the use of COTS and FPGA; thus, many possible types of UAVs could be manufactured on-site and on-demand. Nonetheless, further research is needed and additional work may be needed to realize the potential of the CONOPS, given that the use of additive manufacturing systems on a ship (i.e., an unstable platform) has not been thoroughly looked at previously. There are opportunities to work on the design of the UAV to reduce the cognitive workload of the service member and time required to “print” and assemble the UAV onboard ship based on the assessment.

ACKNOWLEDGMENTS

I would like to express my thanks and appreciation to the Republic of Singapore Navy for giving me the opportunity to study Systems Engineering at the Naval Postgraduate School. Specific thanks to the ex-Head of Naval Logistics, ME7 Sng Yeow Liang; the current Head of Naval Logistics, ME7 Low Yong Joo; the Commander Naval Logistics Command, ME7 Andy Tay; the Hd Operational Logistics Group, ME7 Keith Lim; and the former Head of Naval Personnel and current Commander 3rd Flotilla, COL Richard Lim.

Special mention also to Professor Ronald Giachetti for agreeing to be my advisor and for providing the invaluable advice and guidance to strengthen the presentation and flow of the thesis. To Professor Christopher Adams, special thanks for all the guidance and the insights on aircraft combat survivability, which I have continued to develop into shipboard combat survivability, albeit only on the aspects of improving the detection of risks so as to reduce the overall vulnerability. I would also like to put on record my deep appreciation to Professor Barbara Berlitz for helping me navigate the plethora of thesis processing requirements and strengthening the proposal put forth in the thesis.

I would also put on record my heartfelt thanks to my family who have supported me through the many years of overseas study. The time away from home meant that time together is really precious to me. To my departed brother, Mong Xing, you are deeply missed.

No words can describe my heartfelt thanks to you, Keng Wei. The regular commute between Singapore and Monterey, USA, definitely takes a toll on you as I pursue my studies in NPS. Your support for my academic pursuit over the years, your patience, as well as your words of encouragement are golden to me.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

> We can’t solve problems by using the same kind of thinking we used when we created them.
>
> —Albert Einstein (BrainyQuote 2016)

A. BACKGROUND

In the Navy, ships that are deployed in the operational area are often dependent on the available supplies, spare parts (spares), systems and equipment that are embarked onboard. Should a critical spare(s) and/or part(s) not be available, the ship needs to await the delivery in the next nearest port of call, wait for a re-supply ship to deliver the spare to the ship while at sea (e.g., through vertical replenishment) or continue its mission without the spare(s) and/or part(s). The result is degraded performance unless an extremely robust and efficient supply chain is available. Similarly, the ship lacks the capability of having any new and additional parts during its deployment.

B. CHALLENGES FACED BY THE NAVY

When a ship is deployed and in the area of operation, the ship can only proceed with its current equipment. The ship may already be in the final days of its deployment, or it may be starting the deployment. As such, the systems and equipment may be due for maintenance and would have varying levels of operational readiness. For instance, the helicopter loaded when the ship is deployed may only have limited flight hours left before the next major servicing. It may require parts, special tools and equipment as well as depot-level skills that may only be available in the naval bases. Thus, even though the ship may be re-deployed from its current patrol area to the operation area, it may have inherent limitations that impede full accomplishment of the mission. An example where such immediate deployments or re-deployments occur is in response to a civil emergency. The cases of humanitarian and disaster relief operations following the tsunami on Boxing Day 2004 in Banda Aceh and the tsunami in 2011 in Japan are examples.

Considering this from the Navy level, it is also possible that a capability solution to an operation may become available after the ship is deployed. To manufacture and have the implemented solution delivered to the ship would be challenging, given the need for a robust

supply chain and the potential of the items being damaged while in transit. Furthermore, the items may take weeks before they are delivered.

Conversely, a technical solution may be available, but it will take months before the first article can be produced and put to operational use. This epitomizes what Donald Rumsfeld said, "As you know, you go to war with the Army you have. They're not the Army you might want or wish to have at a later time." (Kristol 2004, A33) Thus, no matter how well-equipped the ship is and how advanced the technologies may be, there will always be the inherent limitations of available spares, reliance on a robust supply chain, and the limitations of going to an operational theater merely with the ship's current equipment.

C. PROPOSED WAY AHEAD

Recognizing this inherent limitation is the core impetus for the thesis. The thesis posits an additive manufacturing technique to build unmanned systems on demand. The thesis is motivated by the fact that such approaches have been done by NASA, such as when a wrench designed on earth was successfully printed at the International Space Station (ISS). In the trial, the wrench was designed on earth and transmitted to the ISS, where it was printed in four hours. From the design of the wrench to the ISS being equipped with the wrench, a total of only seven days were required (Harbaugh 2015).

The thesis thus posits the use of an additive manufacturing technique to be used onboard naval vessels. With 3D printing equipment on board, a ship can access a capability solution to an operation by downloading a design for unmanned systems, printing and then operating (DPO) the unmanned system as and when required. The solution could be in the form of tools, spares, systems or equipment.

D. VALUES PROPOSITION

The values proposition of the thesis is that ships would no longer be limited by their current equipment, or by what spares they carry. There are three key values proposition for DPO through additive manufacturing.

1. Value Proposition 1—Tactical and Operational Flexibility

At the tactical level, as long as the ship is equipped with the additive manufacturing system, it could overcome both the limitation of time and distance where it could download and print what it needs, when it is needed. If the design is available, the printed material fulfills the intended function(s) of any missing item, assuming it is of the right material properties. At the operational level, the force commander could have flexibility in employing a new concept of operations (CONOPS). When the ship is required to be equipped with new capabilities over and above her existing capabilities, it could tap into the repertoire of unmanned systems designs in the Department of Defense (DOD) network, where a design could be downloaded, printed and operated from the ship without the associated concerns about supply chain or production time. Such an equipping approach could lead to more effective use of resources and operational flexibility, while (1) preserving the element of tactical and/or operational surprise over the ship's potential adversary and (2) dislocating the adversary's intelligence gathering effort while tilting the relative combat power in favor of the ship's own forces. This is because the intelligence gathering on the current force structure and capabilities would not be possible with something that is only available as a design, as opposed to a system that is already in existence and deployed for operational use.

2. Value Proposition 2—Just-In-Time Production and Rapid Equipping, Offering Strategic Flexibility

Beyond the tactical and operational flexibility the approach offers at the ship level, the just-in-time (JIT) production and rapid equipping also offers strategic flexibility. There are also benefits to the areas of capability induction, logistics and acquisition, with potential strategic advantages through resource prioritization and budget allocation.

a. JIT Production

The use of additive manufacturing challenges the organization to expend resources in a far more productive way than that envisioned at the point in time when a capability need arises; it allows the organization to decide whether the capabilities should be acquired, or only acquired when needed through DPO with additive manufacturing (Geiger 2000, 10).

Systems development technique could now take the form of spiral development but without the risk of uncertain cost, schedule and performance. It could also contribute toward withholding the decision on the system to acquire or to print, while acquiring only common modules or parts but delaying their use (e.g., through the concept of delayed differentiation that will be introduced in the thesis to enable flexibility in system employment). By not owning the system now or using up the budget to obtain it prematurely, there is a possibility of having something better at a later stage. This could result in a system whose performance is enhanced with better range, better durability, higher payload, and/or better reliability. So, the benefit is that the ships no longer need to carry inventory of finished parts; they just need to carry the inventory of raw materials.

b. Strategic Flexibility

With the proposed use of an additive manufacturing system, it is possible to shorten the timeline from concept to reality, from the design desk to the operational theater, or from "file to form" without going through the production and associated manufacturing and supply chain limitations. This could be the next S curve for the evolution of ships' equipping and capability design. It will enable dynamically configurable mission capabilities and, correspondingly, a dynamic mission envelope where the rapid concept to employment could be realized immediately through additive manufacturing at sea. With each ship being equipped with an additive manufacturing system, distributed manufacturing could be implemented, thereby creating further strategic flexibility over resource use and capabilities employment.

3. Value Proposition 3—Minimal Investment in Rapidly Evolving Systems

The use of additive manufacturing enables rapid prototyping to validate and verify a conceptual design through low-volume production, yet with a lower one-off non-recurrent cost that may otherwise be prohibitive. As a result, a capability can be designed, printed, trialed and refined without actually having it fielded for operational use. The design can continue to evolve to incorporate the latest in the design for a certain capability area(s)/domain(s), such as a low-drag and low-signature geometric design for an airframe to be used for the latest UAV. This could all be accomplished in the design office and as a trial unit. Furthermore, a newest model of a captured unit from the adversary could be studied and rapidly adapted for that ship's own use

without being encumbered by existing systems, limitations of traditional manufacturing and production processes, or associated cost. In effect, the DPO approach allows the Navy to design and build one (or even no) system. When the technology or designs improve, they can just improve the design. DPO therefore allows following the evolution of technology without large investments in materials along the way.

E. THESIS ORGANIZATION

There are tactical, operational, strategic and cost benefits to the realization of additive manufacturing techniques. The thesis discusses potential applications of carrying out additive manufacturing of UAVs while the ship is underway. Through the explorations of UAVs, technological possibilities as well as the possible impediments to additive manufacturing could be further identified. The thesis is organized as follows:

Chapter I discuss the impetus of DPO and the benefits when applied to the naval domain.

Chapter II examines the application of DPO to unmanned systems, specifically the unmanned aerial systems and its application in the naval domain. It provides an introduction to the unmanned systems and their functional hierarchy.

Chapter III discusses the available technologies and techniques for the additive manufacturing of UAVs as and when required. These are the technological building blocks and the enablers to realize DPO using additive manufacturing. The concept of delayed differentiation is also discussed.

Chapter IV explores the possible options to realize DPO and the additive manufacturing of UAVs when the ship is underway, as and when required. It builds upon the technological building blocks discussed in Chapter III and provides a context for how DPO and additive manufacturing could be realized.

Chapter V proposes the concept of operations (CONOPS) that could be employed by the ship utilizing the DPO concept through additive manufacturing and delayed differentiation. CONOPS using UAVs to improve ship survivability will be discussed.

Chapter VI discusses the feasibility for the in-situ manufacturing of UAVs, the time required to additively manufacture a UAV, the capabilities needed onboard the ship and the

COTS required to realize the rapid manufacturing of a UAV onboard ship. The discussion includes the macro assessment of the reliability of the UAV using analytical models that are built to support the assessment.

Chapter VII concludes the thesis. Further areas of research are also identified.

II. UNMANNED SYSTEMS—THEIR PROJECTED USES AND A CANDIDATE FOR DPO USING ADDITIVE MANUFACTURING

The use of unmanned systems by militaries and private organizations has been increasing steadily. This thesis focuses on unmanned aerial vehicles (UAV). There are three sections to this chapter. The first section covers the uses of UAVs and the concerns surrounding their uses to provide a backdrop to the possible and projected future uses. The second section provides a discussion on the case for DPO using additive manufacturing of UAVs. Section three provides a discussion on the types of UAVs, their classification, and their functional hierarchy. The discussion on the functional hierarchy forms the basis for identifying the functions and modules that the DPO approach will need to address.

A. SECTION 1: USES OF THE UAV AND THE CONCERNS SURROUNDING THOSE USES

1. Background

Over the past two decades, UAVs have been used in increasing numbers. Since the first operational deployment of the MQ-1 Predator during Operation Deliberate Force in 1995 to its use in 2011 for Operation Unified Protector over Libya, UAV flight hours grew exponentially because they provide distinctive capabilities with reduced risk such as extensive time-on-station in comparison with manned systems (Joint Air Power Competence Centre [JAPCC] 2014, iii).

In 2014, there are approximately 80 countries operating UAVs as compared to 41 countries a decade earlier. Of the 80 counties operating the UAV, fewer than a dozen operate armed UAVs. Both the trend of owning UAVs and the use of armed UAVs is expected to continue. Concurrently, an increasing number of countries are undertaking indigenous development of their own UAVs or actively trying to achieve UAV technology (JAPCC 2014, 16).

Given the past trajectory, the number of potential applications is poised to increase with ongoing advancements in technology, increasing operational experience and a growing awareness and hence interest in UAV capabilities. The latest development includes the use of an additive manufacturing approach for the development of UAVs. Such capability to “print a UAV” further reinforces the growth trend in UAV uses.

2. Current Uses

UAVs are used by both civilian industries and military forces.

a. Military Uses of the UAV

The uses of UAVs have progressed from intelligence, surveillance and reconnaissance (ISR) to the launch of weapons (e.g., the Predator UAV). The future of UAVs includes the development of unmanned combat aerial vehicles (UCAV), which are capable of high maneuverability that could be difficult or impossible to undertake by manned aircraft. High maneuverability is necessary to execute a tight turn or high-G maneuver to avoid or “break” a missile lock. While the design of a manned aircraft may be capable of withstanding such high G-maneuvers, the pilot may not be able to withstand the resultant gravitational force acting on his body and may suffer a gravity-induced loss of consciousness. The momentary loss of control by the pilot may affect aircraft survivability and impact the fulfillment of the assigned mission(s).

3. Projected Uses

UAV technology is getting lighter and more sophisticated. It is projected that future UAVs will be more autonomous, with capabilities to autonomously take-off, land, taxi and even put themselves away (Savitz et al. 2013, 37). The UAV could also select the target autonomously, with human intervention required only for the decision making. Amongst these benefits, one of the key appeals is that UAVs keep soldiers from getting hurt (Savitz et al. 2013, 37). Additionally, their employment would lead to a reduction in “tactical and operational risks relative to current practices. A reduction in operational risk could allow a more aggressive posture that would force an adversary to change tactics or increase resource expenditures” (Savitz et al. 2013, 37).

The use of UAVs will continue to offer many possibilities. A list of possible military applications is listed below. It is not an exhaustive list and does not represent the full potential of what the UAV could undertake.

1. Deep Penetration—“designed for full electromagnetic stealth, designated to conduct reconnaissance and air strikes deep inside enemy territory” (JAPCC 2014, 3)

2. Combat—“designed for high G-forces and maneuverability, designated to conduct air-to-air and air-to-ground combat in non-permissive and hostile air environments” (JAPCC 2014, 4)

3. Swarm—“designed for expendability and operating in large numbers, forming a swarm” (JAPCC 2014, 4)

4. Conduct of combat surveillance over hostile area

5. Conduct of over the horizon targeting, allowing the firing platform to be positioned at a safe distance from counter-attack

6. Wide area surveillance using multiple UAVs

7. Surveillance operations during maritime transit over areas of high traffic density (such as the Malacca Straits) to achieve comprehensive maritime awareness and hence improve ship’s survivability—this will be elaborated and discussed in Chapter IV on the proposed CONOPS for using UAVs

8. Conduct of “anti-access/anti-denial mission (A2/AD), particularly in military deception, information operations, electronic warfare, and cyberwarfare mission” (Savitz et al. 2013, 33)

9. Destruction of targets—A corollary of this is the suggestion by RAND to use a USV as a “surface torpedo” to ram into a target and explosively detonate itself; an approach that mirrors the attack on the USS *Cole* (DDG 67) in 2000 (Savitz et al. 2013, 18)

10. Decoy platforms—to mask or hide own forces intent, to divert adversary’s attention and resources so as to gain tactical or strategic advantage

11. Rebroadcast platform—platform for extending communication range

12. Extending the supply chain– delivery of mission-essential items (such as spares, medical supplies) from main support area to ship at sea

Projecting ahead, a possible trajectory is the proliferation of UCAVs operating alongside manned aircraft, where the UCAV may be utilized for all dangerous tasks such as air interdiction, suppression of enemy air defenses, conduct of escort jamming, or deploying a deep strike.

Beyond ISR and the envisaged capabilities that could be undertaken by UCAV, the UAV could also be used in support of humanitarian and disaster relief (HADR) operations. An example is the use of UAVs to conduct search and locate (SAL) operations in support of search and rescue (SAR) operations. The Republic of Singapore Navy (RSN) conducted a SAL for

Malaysia Airlines Flight MH370, which disappeared shortly after it took off from Kuala Lumpur International Airport for its journey to Beijing, China. The search areas for MH370 spanned the South China Sea, Gulf of Thailand, Malacca Straits and Andaman Sea, as shown in Figure 1. This necessitated a huge amount of resources and search assets to locate the downed aircraft before SAR could be possible. Assets in such situations, even if deployed, may be inadequate to cover the vast area within the “golden hours” following an incident when the chances of locating survivors remain high. New uses of the UAV were adopted by the RSN to conduct the search for the aircraft in response to the SAL effort. See Figure 2.

Figure 1. Flight Path of Malaysia Airlines Flight MH370. Source: Wikimedia Commons (2014).

Figure 2. Use of UAV Onboard Republic of Singapore Navy Missile Corvette. Source: Chua (2014).

Another possible use for the UAV is as an unmanned observation platform for assessment of hazardous areas as opposed to using a manned observation platform. This is especially relevant for the observations and subsequent work on the Fukushima nuclear reactor in Japan after the tsunami. The UAV could also be deployed to search over vast areas for survivors of the tsunami. Covering a vast area requires a large number of UAVs to increase the chances of finding survivors in the shortest possible time before they succumb to their injuries or the environment.

4. Unmanned versus Manned Aircraft

The increasing trend of UAV use is supported by the increase in capabilities of UAVs and their inherent advantages compared to manned aircraft. Being unmanned, the UAV is not required to carry any life support system, protection system, armoring, ejection system, or defensive system to ensure its safe return to home base. The removal of such requirements for the UAV translates to the removal of the need for a higher level of safety requirements and the qualification needs for the sustenance and protection of the pilot. In its place, the UAV can carry payloads such as additional fuel, batteries, sensors and/or weapons, thereby enhancing its endurance, capability and/or lethality.

For instance, a UAV such as the Predator is optimized for long dwell time but not for speed. As such, it is propeller driven and the fuel consumption is much more economical than manned aircraft. It thus has higher endurance and range. On the other hand, a manned aircraft is designed for speed, payload and survivability and thus is limited in dwell time and, correspondingly, operational range in comparison to the Predator UAV. Concomitantly, there is a reduction in UAV acquisition cost from the lesser need for auxiliary systems for the sustenance and protection of the pilot. The cost savings is extended to the operation and support phase where there is no requirement for upkeep of the operational availability of the auxiliary systems.

5. Challenges of Using UAVs

The development and proliferation of UAV has its advantages. Nonetheless, there are also challenges.

Operating in the naval environment also presents challenges in the launching and recovery of the UAV, especially in bad sea conditions (such as sea state 3 and above). The UAV

could be easily damaged in the process, where the repair and replacement would take time and impact the operational availability of the UAV.

In addition to cost and operational availability, there are also implementation timelines that affect when the UAV is introduced into tactical operations. From the identification of needs until the actual equipping, there will be a wait time before the ships are finally equipped with the UAV, if it is a fleet-wide implementation. With the equipping, a supply chain will need to be established or strengthened and training for operators and maintainers will need to be conducted. This is in addition to ensuring the UAV's through-life supportability is addressed, covering aspects such as adequacy of spares, UAV reliability and assurance of the continuity of support through addressing item obsolescence as it occurs.

Beyond the considerations of UAV use by singular or coalition forces, challenges of UAV use and exploitation by the potential adversary need to be considered. For rogue states or non-state organizations who desire the use of UAVs, they may obtain an alliance UAV, reverse engineer it and exploit the information to copy the technology and develop systems or countermeasures. Iran, for example, is actively researching methods to reduce the detectability of its UAV (JAPCC 2014, 16). On the other hand, there are other ramifications for the use of UAV. For instance, an insurgent force may score a strategic communications victory by displaying a captured UAV in their propaganda. Therefore, recovery or destruction of any lost UAV is considered a high priority mission due to security and strategic concerns (JAPCC 2014, 16). This might pose a tactical constraint of not using the UAV against such adversaries for fear that they may capture, reverse engineer and exploit the UAV technology.

Next, the tactics and employment of UAVs are still in the early stages of development. While UAVs may be employed for tactical surveillance, the number of UAVs employed may be limited. Additionally, there are also tactical and regulatory challenges with respect to the operations of UAVs in and around the national air space, and the potential challenges of encroaching into the civilian airspace.

Finally, unmanned does not mean that it is not being manned; it is just that the operators are operating the unmanned systems remotely. The level of autonomy of the UAV may not be at the level of maturity where the ship can operate many UAVs autonomously without constraining

its own operations. This places a limit on the number of UAVs that the militaries could own and operate at any one time.

B. SECTION 2—THE CASE FOR ADDITIVE MANUFACTURING OF UAVS

The limitation of resources becomes obvious when viewed within the context that militaries are taking on an expanding spectrum of tasks that span the peace-to-war continuum, balancing these duties against finite manpower, financial and physical resources (Figure 3).

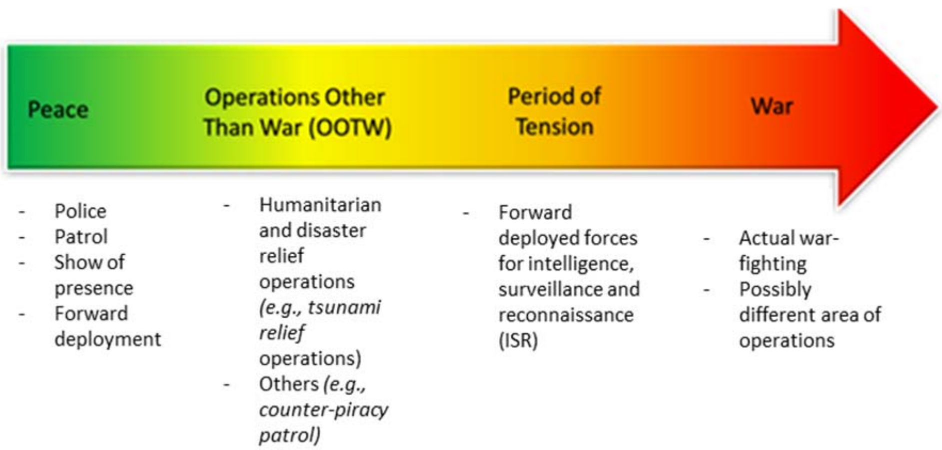


Figure 3. Tasks Undertaken by the Military Across the Peace-to-War Continuum.

Figure 3 provides a snapshot of the tasks to be undertaken by the military. The point to note is that the focus varies in different phases of the peace-to-war continuum. Correspondingly, the resource and capabilities requirements also vary when the military is asked to carry out a humanitarian and disaster relief (HADR) operation where the resources required can be radically different from the resources and capabilities required for war. Additionally, the resources required in normal peacetime training and exercises are likely to be much fewer than those required during HADR or war. These necessitate the rapid scaling up of military hardware such as the UAV, weapons and/or sensor systems, and associated spares as well as their distribution and equipping to the combatant forces. The upkeep of the military to be able to perform the tasks spanning the peace-to-war continuum requires long-term planning, capability acquisition and induction, maintenance and sustenance of the capabilities. It requires ensuring a resilient supply chain network to provide for mission equipping when and where it is needed. DPO CONOPS in

this aspect provide the flexibility to overcome the challenges of long-term planning, capability acquisition and sustenance.

The employment of unmanned technology coupled with additive manufacturing to augment the finite resources that are available to the military could potentially alleviate the equipping challenges of the military and allow it to undertake the multitude of tasks in the peace-to-war continuum. The following section discusses the state envisioned and the approach used to enable additive manufacturing.

1. Envisioned State

Cognizant of the limitation of resources, the different capabilities required during different periods across the peace-to-war continuum, and the continuous evolution of technology, the envisioned state is to provide the military with the capabilities as and when they are needed. The motivations are:

- **Logistics**: reduce the number of parts to carry and reduce reliance on supply chain
- **Flexibility**: customize on demand
- **Efficient use of resources**: build only what is needed

For this thesis, the envisioned state is that the ship could obtain a UAV design even when it is at sea. The design could be obtained from the DOD's repertoire of available UAV designs (through the satellite or communication networks), where it is then manufactured in-situ and deployed for the operation the ship is tasked to undertake. Once the task is completed, the UAV could be disposed of or recycled for future use. Such an approach therefore allows the utilization of the required capability as and when required, tailored to the mission and minimizing waste after completion of the mission. A three-stage process is envisioned: design, print and operate.

a. Design

The design stage encompasses the design of the UAV or capabilities. It could include the actual research and development of a new UAV design, or modification and/or refinement of an existing UAV design. Once the design is completed, it could be tested with any shortcomings identified, mitigated and refined before the design is fixed. At this stage, instead of proceeding to

the development of the UAV from the design, the design could then be made available through a central repository where it could be downloaded and printed as and when required. The design activities could be carried out in advance of its actual requirement, or it could be downloaded and/or modified onboard ship, or remotely from the ship such as from a shore installation when the need arises to tailor the UAV for the specific mission. The modification of an existing design is expected to take a much shorter time than the full design activity.

b. Print

Once the desired UAV design is downloaded, the UAV could then be manufactured onboard the ship. Given the build volume of existing additive manufacturing systems, there may be a need for the UAV to be broken down into its constituent parts to be additively manufactured before it is assembled into its final form. As such, this stage involves not just the "printing," but also the task of post-processing, assembling the constituent parts to form the UAV and post-integration testing to verify its functionality.

c. Operate

The third stage will be the operation of the UAV. Once the UAV is printed and a system check is conducted to ensure it is functional, it is ready for the operational employment. Collectively, the three-stage process will be referred to as DPO in the following discussion.

Navy ships may be deployed at sea for prolonged durations. The use of a resupply ship could extend a ship's endurance at sea. This provides strategic flexibility for the military commander. The ship could be deployed from one area of operation to another through mission tasking. The ship may or may not be equipped with the required capabilities to execute the assigned mission, however. There could be a large number of possible UAVs that could be employed in the naval domain. To exploit the capabilities and advantages enabled by each UAV means that the ship will need to carry a large number of UAVs as well as spares to ensure its operational availability; these will, however, result in an increase in equipping and ownership cost, thereby imposing a constraint on the number of UAVs that could eventually be deployed. With DPO, these could be overcome by the ship being equipped only with the additive manufacturing system and the raw materials to enable the additive manufacturing of the UAVs while it is out at sea.

The use of DPO has the added benefit of enabling the use of spiral development to improve and acquire capabilities not envisioned for the product in its initial introduction (Grady 2010, 23). Nonetheless, the UAV will have the constituent parts and the operational interaction with the environment, albeit it may have different forms and functions. The next section explores the types of UAVs, their classification, and the range of considerations that affects the UAV design.

Additionally, the use of DPO offers the opportunity to scale up rapidly the number of UAVs for use in mission(s) and provides a key advantage to the military. The advantages are:

1. preventing the situation where the military is locked into the current technology versus the exploitation of the latest technological evolutions
2. the ability to match capabilities with the development of new concepts of operation necessitating additional UAVs
3. the increase in relative combat power with the capability to rapidly print and use or print and repair, thus unlocking future concepts of operations and/or courses of action development while not being tied to the procurement process, manufacturing lead time, or supply chain to equip and/or to re-supply ships and/or forces in the operational theater
4. the ability to rapidly scale up the total number of available UAVs for missions without the associated cost of ownership associated with the planned and corrective maintenance, the procurement and manufacturing lead time. When the UAV is no longer needed, the number could be scaled down (the proposed concept is a “use and throw” or a “use then recycle” approach), thereby minimizing the total cost of ownership through avoiding the cost to perform scheduled and unscheduled maintenance.

The capability to print and use may lead to a paradigm shift toward a single use or “use and throw” systems versus the current “use and maintain” approach. From the operation and support perspective, the current approach requires spares to be stocked, maintenance personnel to be trained and preventive and corrective maintenance to be performed on the UAV to maintain a certain level of operational availability, A_o. One key aspect affecting A_o is the reliability of the system. In comparison, the systems reliability for a “use and throw system” may not be as stringent; hence, the approach allows more affordable components to be used, while at the same time avoiding the need for maintenance. This would lead to the lowering of the overall cost of ownership through the possible reduction in the total cost of upkeep.

2. Enabling Approach

The envisioned state could be actualized through the use of additive manufacturing techniques, more commonly known as three-dimensional (3D) printing. This may be augmented with the use of commercial-off-the-shelf (COTS) items as well as programmable gate arrays for the electronics components. Chapter III provides further exploration and discussion on the enabling technologies that form the building blocks to actualize the DPO CONOPS for additive manufacturing of UAVs onboard ship.

C. SECTION 3—TYPES OF UAVS, THEIR CLASSIFICATION AND THEIR FUNCTIONAL HIERARCHY

Although there are a multitude of UAV designs, there are currently no widely accepted common classifications of UAVs. This is due to the plethora "of capabilities, sizes and operating characteristics" of UAVs that are available or becoming available (Gupta, Ghonge, and Jawandhiya 2013, 1647). There are also no firm and fixed design specifications governing the design and construction of the UAVs. Neither are there unifying regulations with respect to the physical implementation and design of the UAVs. Such governance and regulations exist to ensure that the safety of the operator and the public are not compromised. There are also other emerging UAVs that may require a finer level of classification other than the use of operating ranges to better understand the research and developmental trajectory. To provide a basis of referring to the UAV design, and in identifying the variation in UAV designs, a summary of the types and classification of UAVs is provided in Table 1 and Table 2.

Table 1. Types of UAV. Adapted from Gupta, Ghonge, and Jawandhiya (2013, 1647).

S/N	Type	Description
1	Fixed Wing	UAVs that require a winged surface for sustained flight and will require a runway to take off and land, or catapult and arresting systems to take off and land, respectively.
2	Rotary Wing	Rotorcraft UAVs that take off and land vertically and have the advantage of high maneuverability, including hovering. They can have one to multiple rotors.
3	Flapping Wing	UAVs that have flexible wings to produce lift.
4	Hybrid	These are UAVs that are capable of taking off vertically, tilting their rotors and/or body and proceeding to fly like an airplane.
5	Blimps	These are UAVs that are typically lighter than air and are balloons or airships.

Table 2. Classification of UAVs. Adapted from Gupta et al. (2013, 1652–1653).

Category	Weight of UAV	Operating Altitude	Mission Radius	Endurance	Altitude	Employment	Typical Use
MICRO	<2kg	Up to 200ft AGL	5km (LOS)	A few hours	Very low altitude	Tactical platoon (single operator)	Reconnaissance*, surveillance
MINI	2-20kg	Up to 3000ft AGL	25km (LOS)	Up to 2 days	Low altitude	Tactical sub-unit (manual launch)	Intelligence and surveillance
SMALL	20-150kg	Up to 5000ft AGL	50km (LOS)	Up to 2 days	Low altitude	Tactical unit (launch systems)	Intelligence and surveillance
TACTICAL	150-600kg	Up to 10,000ft AGL	200km (LOS)	Up to 2 days	Low altitude	Tactical formation	Intelligence and surveillance
MALE	>600kg	Up to 45,000ft AGL	Unlimited (BLOS)	Days/ weeks	Medium altitude	Operational/ theater	Intelligence, surveillance, cargo delivery (weapons)
HALE	>600kg	Up to 65,000ft AGL	Unlimited (BLOS)	Days/ weeks	High altitude	Strategic/ national	Intelligence, surveillance, targeting, signal relay
STRIKE/ COMBAT	>600kg	Up to 65,000ft AGL	Unlimited (BLOS)	Days/ weeks	High altitude	Strategic/ national	Intelligence, surveillance, targeting, signal relay, strike

* Reconnaissance is the "activity to obtain by visual or other detection methods information about what is present or happening at some point or in some areas, and surveillance is the systematic observation of aerospace, surface or subsurface areas, places, persons or things by visual, aural, electronic, photographic or other means" (Gupta et al. 2013, 1652–1653).

Legend and definitions (Gupta et al. 2013, 1652–1653):

AGL	above ground level
LOS	line of sight
BLOS	beyond line of sight
High altitude	over 60,000ft
Medium altitude	18,000—60,000ft
Low altitude	up to 18,000ft
Very low altitude	below 1,000ft
HALE	high altitude long endurance
MALE	medium altitude long endurance
TUAV	medium range or tactical UAV

1. Types of Airframe

The previous section highlighted that there are currently no widely accepted common classification of UAVs. In fact, there are also no restrictions or limitations on the possible configurations of the airframe design. Rather, the airframe design considerations are typically built to fulfill the required speed, payload and range requirements. Austin highlighted that the

"range of airframe configurations for UAV is as diverse as those used for crewed aircraft, and is in fact more since the commercial risk in trying unorthodox solutions is less for the UAV's manufacturer" (Austin 2010, 34). It was reasoned that this is so "principally because the UAV airframes are usually much smaller than crewed aircraft and operators are less likely to have a bias against unorthodox solutions" (Austin 2010, 34). As such, there are many possible types of airframe design. Austin classified airframe configurations into three broad categories for the purpose of classifying the types of airframe that might become available for the UAV. This is shown in Table 3.

Table 3. Three Broad Categories of Possible UAV Airframe Configurations. Source: Austin (2010, 34).

Airframe configurations	Description
Horizontal take-off and landing (HTOL)	This is as opposed to conventional take-off and landing (CTOL) since vertical take-off and landing (VTOL) is no longer unconventional. As such, HTOL is used to refer to aircraft that are required to accelerate horizontally along a runway or strip in order to achieve the required speed for sustained flight.
Vertical take-off and landing (VTOL)	No runway or strip is required.
Hybrids	This is the combination of the attributes of both HTOL and VTOL.

a. HTOL Configurations

The fundamental types of HTOL are shown in Figure 4. It is "determined largely by their means of lift/mass balance and by stability and control" (Austin 2010, 34–35). The differences are summarized in Table 4.

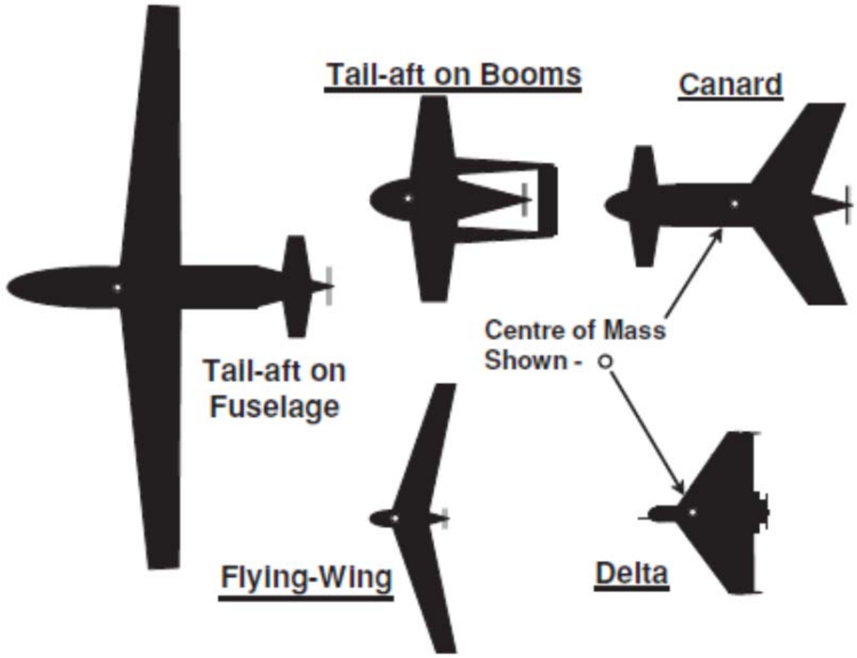


Figure 4. Fundamental Types of HTOL. Source: Austin (2010, 35).

Table 4. Summary of Differences in HTOL Configurations. Adapted from Austin (2010, 35–36).

HTOL configurations	Description
Main wing forward with control surfaces aft	Conventional arrangement; "by far the most ubiquitous. The UAV center of mass is forward of the wing center of lift. This is balanced by a down-load on the tail plane thus providing aerodynamic speed and attitude stability in the horizontal plane."
Canard	A "canard configuration has the horizontal stabilizer, or fore plane, mounted forward of the wing. The aircraft center of mass is forward of the wing. The balance is achieved with the fore plane generating positive lift."
Flying wing or "tailless"	"Sweep-back" wings with tip aero foils that "have a greatly reduced incidence compared with the aero foils of the inner wing to ensure the aircraft nose rises, the center of lift of the wing moves rearwards, thus returning the aircraft to its original attitude."
Delta-wing	The delta-wing configuration gives a "rugged airframe for skid or parachute landings, without the lighter and more vulnerable tail." It, however, has "poor lift distribution, resulting in higher induced drag that is exacerbated by its higher span loading."

All configurations “have the power-plant at the rear of the fuselage” so as to “free the front of the aircraft for the installation of the payload to have an unobstructed view forward,” which is ideal for ISR missions (Austin 2010, 34–35).

b. VTOL Configurations

There are various VTOL configurations. They are driven by the counteraction of the torque by the rotor to achieve stability in flight. Figure 5 shows the various configurations (Austin 2010, 37). The elaborations are shown in Table 5.

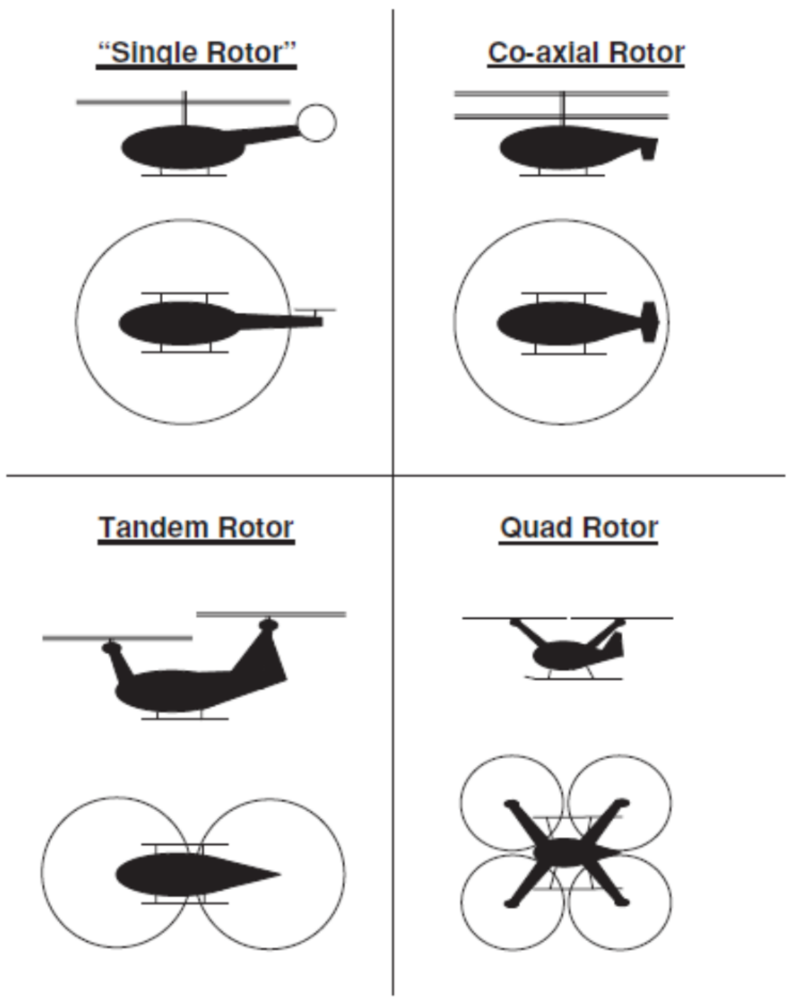


Figure 5. Fundamental Types of VTOL. Source: Austin (2010, 37).

Table 5. Summary of Differences in VTOL Configurations. Adapted from Austin (2010, 37–38).

VTOL configurations	Description
Single rotor	The “torque of the main rotor tends to turn the aircraft body in the opposite rotational direction to the rotor.” This “is counteracted by a smaller, side-thrusting tail rotor.” The tail rotor “typically adds about a further 10% onto the main rotor power demands.”
Tandem rotor	This is the configuration where “there is a strong scale effect on the size of the helicopter rotors where the ratio of the rotor mass to lift increases strongly with the larger rotor sizes” and is often used by “heavier aircraft. It is more efficient to fit two smaller rotors than one large rotor to aircraft above a certain all up mass.” In comparison with the single rotor configuration, the tandem rotor “configuration is more symmetric in control” and is more power efficient.
Coaxial rotor	This configuration is compact with no vulnerable tail rotor. This is an advantage as the tail rotor might be fragile or susceptible to hitting ground objects. Additionally, the configuration offers aerodynamic symmetry, contributing toward efficiency of power. The configuration also offers the “versatility of having alternative body designs for different applications.”
Quad rotor	The quad-rotor design is radically different from the VTOL design, which uses “rotor-head control systems where both cyclic and collective pitch changes to the rotor blades as the means of aircraft control.” There is no cyclic and collective pitch changes for quad rotors and there is no need for a mechanical transmission system. Instead, each of the rotors is individually driven. Flight control is achieved through variation in the speed of the rotor.

c. *Hybrids*

> The helicopter has been shown to be the most efficient of the heavier-than-air aircraft for hover flight. They are however limited in cruise speed to the order of 200 knots or 370 km/hr by the stalling of the retreating blade(s). For longer-range missions it is necessary to have the aircraft cruise at higher speed to achieve an acceptable response time to the target or area of patrol. However, the ability to take off and land vertically is a valued asset. (Austin 2010, 40)

This is the motivation that led to combining the capability of the VTOL and the HTOL. The available configurations are shown in Figure 6 and described in Table 6.

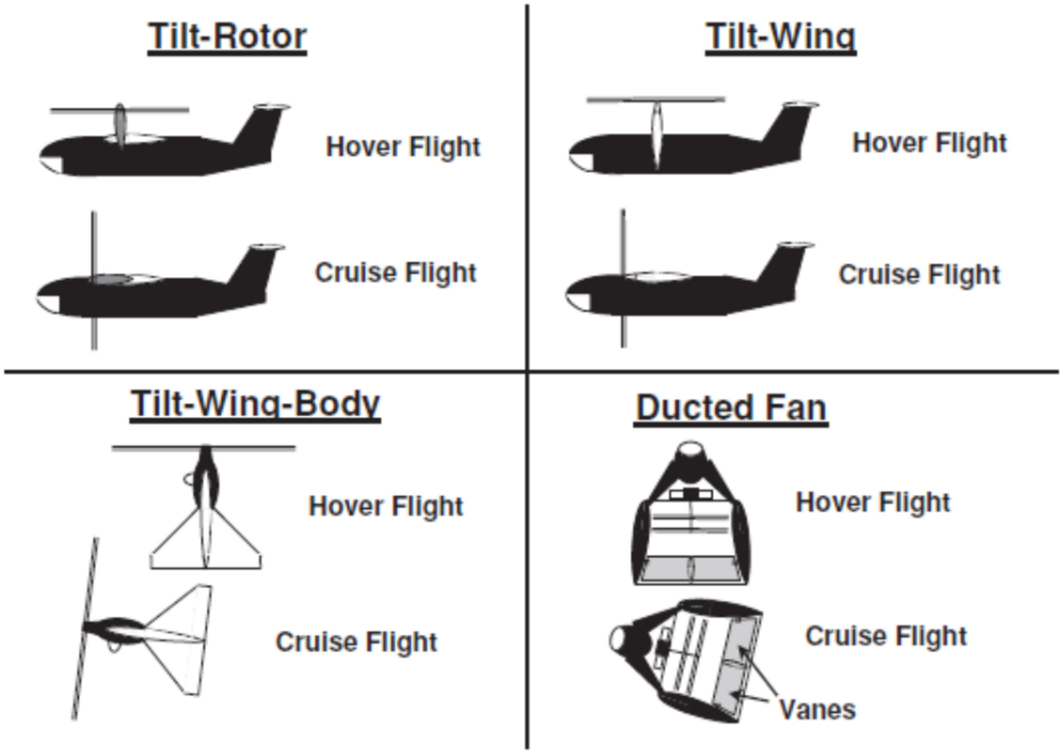


Figure 6. Fundamental Types of Hybrid. Source: Austin (2010, 40).

Table 6. Summary of Differences in Hybrid Configurations. Adapted from Austin (2010, 42)

Hybrid configuration	Description
Convertible rotor	"The rotors are horizontal in vertical flight, but tilt forward through 90º, effectively becoming propellers for cruise flight."
Ducted fan	The UAV "encloses its "thruster" within a duct. The thruster is called a "fan" as it is of constrained diameter and will be of high solidity (i.e., the ratio of blade area to disc area.)"

2. Other UAV Considerations

a. Payload

The layout, size and all-up-mass (AUM) of the UAV is dependent on the size, mass of the payload and its requirement for electrical power supplies. The payload may range in mass from a fraction of a kilogram up to 100 kg and in volume from a few cubic centimeters to more than a cubic meter, especially in the case of armed air vehicles. (Austin 2010, 21)

Additionally,

> the position of the payload may also be a significant factor in the configuration and layout of the airframe. For example, imaging payloads for surveillance may require a full hemispheric field of view, whereas a communication relay UAV may require a large surface area for antennas. (Austin 2010, 21)

On the other hand, if there are requirements for the payload to be jettisoned or where weapons may be required to be launched from the UAV, then the positioning of the payload may be required to be close to the center of mass of the air vehicle (Austin 2010, 21).

b. Endurance

The flight endurance demanded is dependent on the mission type. It could range from

> one hr for a close-range surveillance system to more than 24 hours for a long-range surveillance or airborne early warning (AEW) system. Correspondingly, the volume and mass of the fuel load to be carried will be a function of the required endurance, the efficiency of the aircraft's aerodynamics and its power-plant. The mass of the fuel to be carried may be as low as 10% of the aircraft AUM for close-range UAV, but rising to almost 50% for the long-endurance aircraft, thus being a significant driver in determining the AUM of the aircraft. (Austin 2010, 21)

c. Radius of Action

Related to the endurance aspect, as well as the mission type, is the radius of action or the operating range of the UAV. It may be limited by the amount of fuel or battery capacity, its efficiency and speed. Beside the flight aspect, it is also affected by the range of its communication link, which is in turn dependent on the "power, frequency, reliability and sophistication of its communication links" (Austin 2010, 21). In addition, the design and positioning of the radio antennas will impact the communication range and could have an effect on the choice of UAV configuration. The radius of action therefore has "a significant impact on the choice of navigation equipment affecting both aircraft and control station" (Austin 2010, 21).

d. Speed Range

The speed range is dependent on the speed of response required and could typically range from

- 0 to 100 knots for a close-range surveillance role
- 0 to 150 knots for off-board naval roles

- 80 to 500 knots for long-range surveillance and airborne early warning roles
- 100 knots to Mach 1-plus for future interception and/or interdiction role (Austin 2010, 21)

The type of mission affects the speed range, and the speed range in turn determines the configuration and propulsive power of the UAV. This is summarized in Figure 7, which indicates the aircraft configuration that is most appropriate to the speed ranges. It can be used as an assessment of the type of airframe that is suitable for the UAV. In Figure 7, relative efficiency is used as speed associated with cost through the fuel consumption as well as airframe complexity (Austin 2010, 21–22).

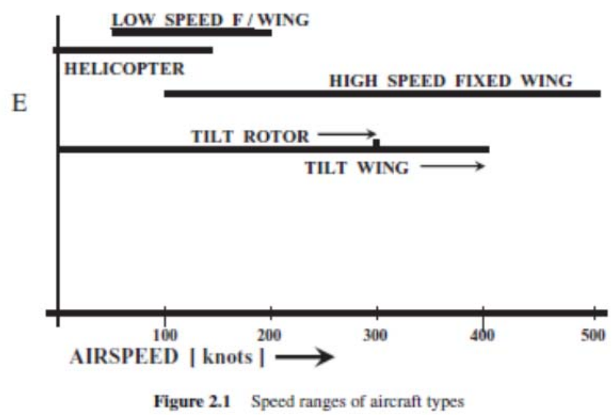


Figure 7. Relative Efficiency versus Speed Ranges of Aircraft Types. Source: Austin (2010, 22).

3. Context Diagram and Functional Hierarchy of the UAV

The UAV will have operational interaction with the environment, though it may have different forms and functions. Having seen the many variations of UAVs with different forms and varied functions, the context diagram is next presented before the functional hierarchy of the UAV is developed. The purpose is to elicit commonalities and differences across different UAVs, thus enabling the identification of the building blocks for realizing the DPO of UAV using additive manufacturing, and use of COTS to enable delayed differentiation. Figure 8 shows the context diagram of the UAV.

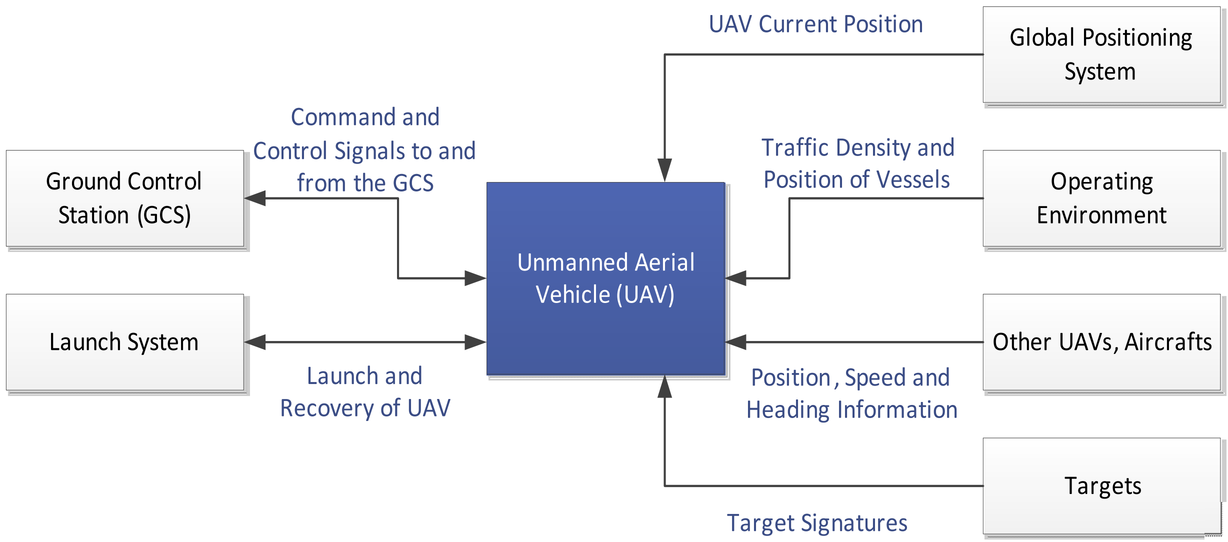


Figure 8. Context Diagram of UAV System.

In developing the context diagram for the UAV, the objective is to determine the interactions between the system and its environment. The diagram shows the energy, material and information going into the systems as a "black-box" and the output it produces. Thus, the function that takes place within the "black-box" will be the focus of the UAV design; which could differ for different mission requirements. The boundaries of the systems were therefore identified based on the systems and entities that have direct impact on the successful conduct of the possible range of UAV mission(s). In developing the context diagram, the focus is on determining the WHAT (is required) first, deferring the HOW (it is implemented) until later. Therefore, the development of the context diagram is conducted at the solution neutral level so as to explore and not constrain the possible solution space as different UAV designs could then be evolved for the fulfillment of different missions. Being at the solution-neutral level also prevents the premature ruling out of innovative ideas in the implementation and/or employment of the UAV through additive manufacturing. There are six external systems identified, of which five interface with the UAV. The following is an elaboration of the UAV context diagram.

a. Ground Control Station

The ground control station (GCS) issues commands to control the UAV. Such commands includes ordering the UAV to proceed to a certain location; maintain or adjust to a certain speed, heading and altitude; inspect suspicious targets; and commence or terminate the mission. It also

includes the control of the UAV's payload, as well as controlling the UAV to provide certain information back to the GCS. Such information may include the UAV's health, remaining energy level, sensor information, etc.

b. Launch System

This is the system to launch and recover the UAV from the ship. It could include a launch rail to catapult the UAV to a certain speed and altitude for the HTOL type of UAV, or it could just be an open space onboard the ship for which the VTOL or hybrid configuration type of UAV could safely take off and land.

c. Global Positioning System

The global positioning system (GPS) provides the position information of the UAV to enable safe and reliable navigation.

d. Operating Environment

This represents the traffic density at the immediate launch area, and the operating condition at the desired operating area. The operating environment could be day/night with good to restricted visibility, as well as the electromagnetic environment that might limit the use of certain frequencies. It could include the number of ships in the vicinity, the proximity to foreign airspace (and thus the regulatory requirements that need to be fulfilled), as well as wind and other weather conditions.

e. Other UAVs, Aircraft

These are the heading, speed and position information of other UAVs and/or aircraft as detected by the UAV's sensor for purpose of collision avoidance. This includes the position of adjacent UAVs operating in the same area (e.g., when operating in swarm).

f. Targets

The target signatures could include the range, speed, location and heading of the air (e.g., UAVs and aircraft) and surface (e.g., ships, seaborne threats, targets) contacts. They are the attributes of the targets that have been detected by the UAV's sensors.

The functional hierarchy of the UAV and the GCS systems are shown in Figure 9 and Figure 10, respectively. The functional description of the UAV systems and the GCS is shown in Table 7 and Table 8, respectively.

Figure 9. Functional Hierarchy of the UAV System—UAV.

Table 7. Functional Description of the UAV.

Item	Description
1.0 Provide Command and Control	The function is to be the central system in the UAV to coordinate the UAV's modules so that they function as an integral whole for the mission. It includes the control of flight, navigation, flight planning, auto-pilot, monitoring of UAV health, transmission of data to the GCS as well as the receipt and interpretation of commands from GCS. It comprises the following sub-functions: **1.1 Monitor UAV's Health**. To continuously monitor own health. It includes the continuous monitoring of own functionalities that include detection of anomalies in operating temperature, electrical power or anomalies from the mechanical interfaces. **1.2 Control UAV's Movement**. To decipher the control signal from the GCS and the navigation system so as to enable control of the UAV's movement.
2.0 Provide Navigation	The function is to provide navigational information to the UAV. It includes the use of GPS and the inertial navigation system (INS), which could be the UAV's primary and secondary navigation system, respectively, to provide a fix on the UAV's current position and speed. The information is used by the onboard command and control module for flight planning and navigation. It comprises the following sub-functions: **2.1 Determine UAV's Position**. To provide own location relative to the environment. This includes the altitude, speed, tilt and roll of the UAV. **2.2 Determine Route (to commanded location)**. To determine the route to take from current position to the desired position. It includes obtaining own position from own function *determine* position.
3.0 Monitor UAV and Target Information	The function is to provide information on the UAV's heading, speed, altitude, orientation (roll, pitch and yaw), and obstacle(s) (if sense and avoid capability is included in the design) in the planned UAV's path. The information will be used by the UAV's command and control module for flight control, path planning, collision avoidance (if included in the design) and ensuring stable flight. It comprises the following sub-functions: **3.1 Provide UAV's Attitude (Orientation and Speed) and Altitude**. To continuously provide the UAV's attitude and altitude so as to enable effective control of the UAV.

Item	Description
	3.2 Provide Target Information (Bearing and Range). To provide target information so as to implement collision avoidance and/or providing the information to the GCS. **3.3 Monitor Own Functionality**. To continuously monitor own functionality, which includes detection of anomalies in operating temperature, electrical power or abnormalities from mechanical interfaces.
4.0 Communicates Internally and Externally	The function is to provide bi-directional link between the UAV and the GCS. It includes the transmission and reception of the UAV command from GCS, and the sending of images, videos, sensor information in general and UAV flight data to the GCS. It comprises the following sub-functions: **4.1 Receive Data and Command**. To receive data and command from GCS or from within UAV. **4.2 Process and Interpret Data**. To process and interpret the data. It includes recovery of the noise-corrupted signal and interpretation of the received data. **4.3 Transmit Data**. To transmit data and command to GCS or within UAV. **4.4 Process Data for Transmission**. To process the data for transmission. It includes coding to ensure low bit error probability.
5.0 Provide Payload Interface	The function is to provide the interface to the payload or physical assets carried by the UAV to execute the intended mission and/or tasks. It would require space, weight and power allocation of the UAV. For example, it would take supply from the power module and provide the sensor data to the communication module where it could be sent to the GCS. In certain situations, the payload may require information interchange with the UAV. As such, its inclusion may impact the safety and/or proper functioning of the UAV (Gupta et al. 2013). Payloads for UAV generally consist of sensors and/or video cameras. Auxiliary payload may include additional power module to extend the range of the UAV or explosives to enable it to function as a guided projectile. As such, the payloads could contribute to sensor integration, decision making, and training. It comprises the following sub-functions: **5.1 Provide Payload Mechanical Interface**. To provide physical interface to external modules.

Item	Description
	5.2 Provide Payload Electrical Interface. To provide electrical interface to external modules. **5.3 Provide Payload Data Interface**. To provide data interface to external modules.
6.0 Provide Power	The function is to provide the energy source to the UAV to power the flight and the onboard modules. The actual system could comprise batteries, solar panel and/or alternator to provide the electrical supply for all the UAV's modules. It comprises the following sub-functions: **6.1 Provide Stored Energy**. To provide stored energy to power the UAV and its modules. **6.2 Provide Alternate Energy Source**. To provide alternate source of energy to the UAV and to power its critical module so that it does not endanger the operators and/or jeopardize mission execution.
7.0 Provide Structures	The function is to provide the aero-structure of the UAV that contains all the necessary modules such as the power, propulsion and mission payload. It also includes the actuators for the control surfaces. It comprises the following sub-function: **7.1 Control Direction**. These may include control surfaces such as the aileron, rudder and the associated actuators and position feedback system for controlling the direction of the UAV.
8.0 Propulsion System	The function is to provide the mechanical power to provide thrust for the UAV. It comprises the following sub-functions: **8.1 Provide Energy Distribution**. To provide the distribution of energy from the energy source to the propulsion plant.

Having covered the functional hierarchy of the UAV, the functional hierarchy of the GCS is next covered.

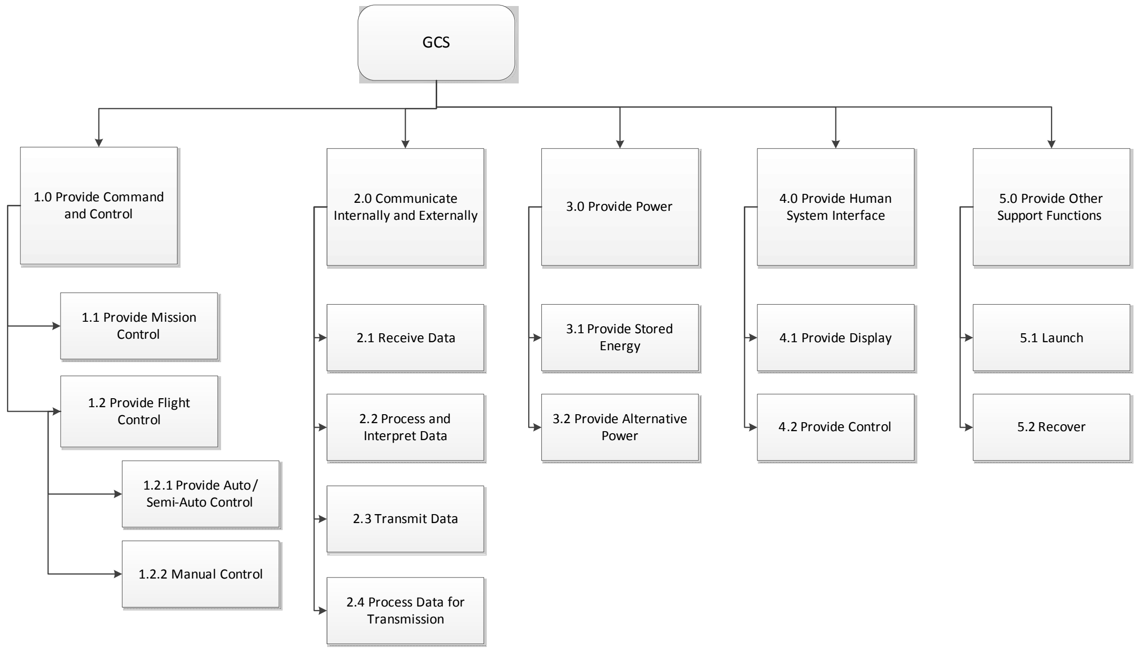


Figure 10. Functional Hierarchy of the UAV System—GCS.

Table 8. Functional Description of the GCS.

Item	Purpose
1.0 Provide Command and Control	The function is to be the central system in the GCS that controls the UAV and coordinates the information exchange between GCS and UAV. It obtains mission parameters and pilot input through the human-machine interface and allows the pilot and operators to control the UAV in real time. The control includes the direction to the mission area, flight profile (such as speed and altitude), control of sensors to obtain target information (such as the pan, tilt and zoom of the electro-optic, infra-red camera), and management of the datalink between GCS and the UAV. It also receives status update from the UAV, location and health of the UAV, sensor information. **1.1 Provide Mission Control.** The function is to provide the planning of the flight profile, which includes the setting of the destination, waypoints, and mission durations for the UAV. It includes the planning of the flight profile. **1.2 Provide Flight Control**. The function is to provide the pilot the control of the UAV during take-off, landing, and target investigation, or as and when flight control is required. It also includes the situation where the autonomous flight control is defective and manual flight control is necessary to pilot the UAV back to the unit operating it. It comprises the following sub-functions: **1.2.1 Provide Auto/Semi-Auto Control**. The system will provide the guidance to the UAV without operator input until it is within a certain

Item	Purpose
	distance (e.g., 100 ft.) from the ship during both take-off and landing. **1.2.2 Manual Control**. The system will require operator control when it is near (e.g., within 100 ft.) the ship during both take-off and landing. The system also allows operator control of the UAV when the auto/ semi-auto control mode is defective.
2.0 Communicate Internally and Externally	The function is to provide the radio and data link to enable bi-directional data transfer capability to allow the UAV to be controlled and for the UAV to send sensor information back to the GCS for situational awareness, sense-making and/or decision making. It comprises the following sub-functions: **2.1 Receive Data and Command**. To receive data and command from within the GCS or data from the UAV. **2.2 Process and Interpret Data**. To process and interpret the data. It includes recovery of the noise-corrupted signal and interpretation of the received data. **2.3 Transmit Data**. To transmit data and command to GCS or within UAV. **2.4 Process Data for Transmission**. To process the data for transmission. It includes coding to ensure low bit error probability.
3.0 Provide Power	The function is to provide power to the entire GCS. It also includes the use of emergency generator and uninterruptible power supply systems to ensure minimal or no disruption during the mission phase so as to ensure successful mission execution. It comprises the following sub-functions: **3.1 Provide Stored Energy**. To provide stored energy to power the GCS and its modules. **3.2 Provide Alternate Energy Source**. To provide alternate source of energy to the GCS to power its critical module so that it does not endanger the operators and/or jeopardize mission execution.
4.0 Provide Human System Interface	The function is to provide the interface to the UAV pilot and sensor operator to control the UAV from the GCS. It comprises the following sub-functions: **4.1 Provide Display**. To process and display the information from the UAV to the operator and allow a comprehensive awareness of the UAV's location and sensor information while enabling a single point of control for the UAV. **4.2 Provide Control**. To provide operators control of the UAV through the GCS.
5.0 Provide Other Support Functions	The function is to provide other support functions for the shipboard use of the UAV. An example is that it enables the safe launch and recovery

Item	Purpose
	of the UAV and comprises the following sub-functions: **5.1 Launch**. To enable the launch of the UAV into the sky. It could include the use of a catapult system to propel the UAV to a speed that allows sustainment of flight before its own propulsion or propellers take over. **5.2 Recover**. To recover the UAV with no damage to the UAV. The recovery system will be used where there is no runway (such as onboard ship) or when the UAV is not designed with landing gear so as to increase the overall payload capability.

From the functional hierarchy for the UAV, it can be assessed that there will be four major categories of items requiring implementation. They are:

1. **Mechanical modules**. These are the structures, control surfaces of the UAV, and launch and recovery system for the UAV onboard ship.
2. **Specialized electronics**. These are the modules for the UAV as well as the GCS. It includes the GPS, sensor modules, navigation modules and communication modules that are generic and can be used for different UAV types.
3. **UAV control electronics**. These are modules for the UAV and the GCS. It is the command and control module that is necessarily context-specific to the type of UAV being employed.
4. **Power modules**. This consists of batteries and/or gasoline.

They are as depicted in the physical architecture. See Figure 11.

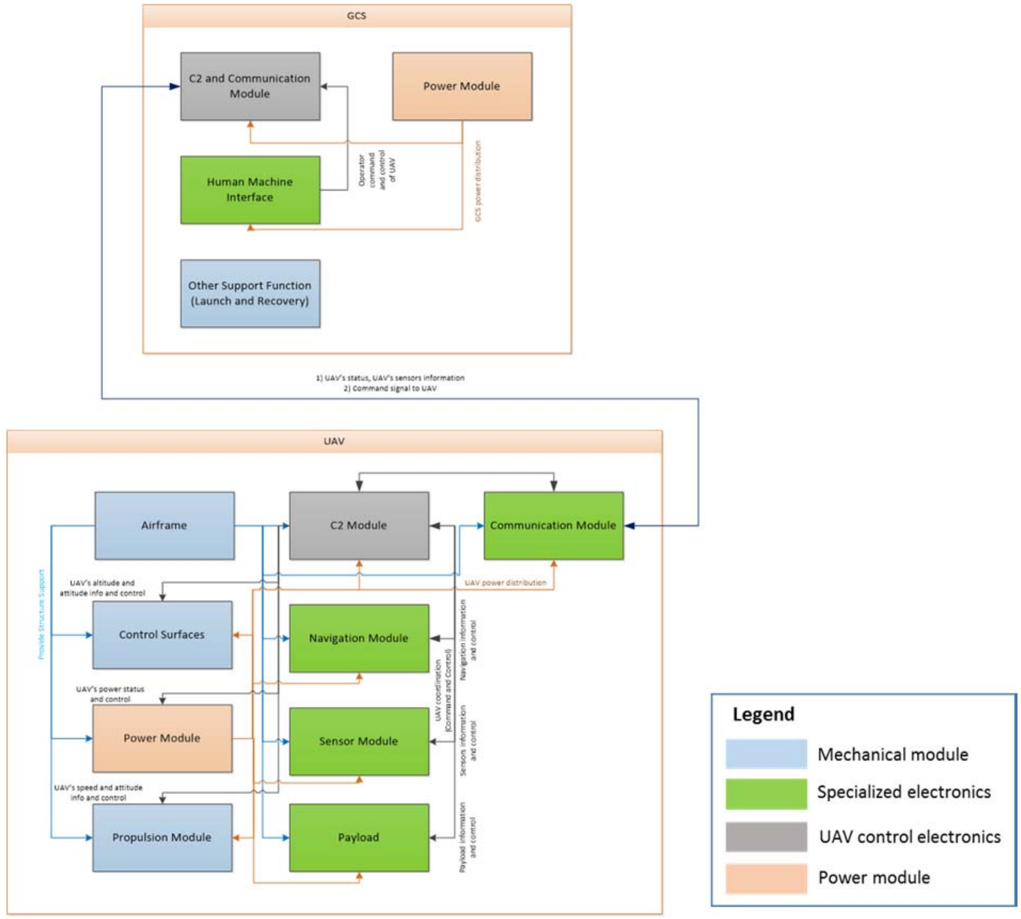


Figure 11. Physical Architecture of the UAV and GCS.

D. SUMMARY

The survey of the UAVs reveals that there can be many permutations to the uses and implementations. The differences in the design of the airframe and its projected utility signal that there is little or no restriction to the ingenuity of approach in implementing the UAV. Being unmanned, it also meant that the consideration of passenger safety as well as the associated requirements with respect to safety and aviation regulations are not as well developed and thus not as tightly regulated, as yet. These helped to spur and promote the exploration of the UAV in various quarters, given the potential benefits it can bring to the industry and the military. The result is that there is increasing interest in the UAV, which in turn drives the design, which in turn means that there will be much improvement. That is, the design is still evolving. As such, understanding the context in which the UAV operates, and the functional hierarchy of the UAV, is quintessential to implementing the espoused DPO CONOPS for UAV.

III. AVAILABLE TECHNIQUES TO REALIZE ADDITIVE MANUFACTURING OF UAVS

With the background and impetus for DPO of UAVs for use in the naval domain covered in Chapter I and II, respectively, this chapter explores the technological trends, opportunities and challenges of the enabling technologies for the DPO of UAVs. The enabling technologies will be those identified to implement the functional hierarchy of the UAV. The building blocks are mapped into the various constituent parts of the UAV in Table 9, initially discussed in Chapter II on the functional hierarchy.

Table 9. Enabling Approach for Implementation of the UAV System.

Item	Categories	Possible Enabling Technologies
UAV—Unmanned Aerial Vehicle		
Command and Control Module	UAV control electronics	Additive manufacturing
Navigation module	Specialized electronics	COTS or FPGA
Sensor Module	Specialized electronics	COTS or FPGA
Communication module	Specialized electronics	COTS or FPGA
Payload	Specialized electronics	COTS
Power Module	Power modules	COTS, possible additive manufacturing
Airframe and Control Surfaces	Mechanical modules	Additive manufacturing
Propulsion System	Mechanical modules	Additive manufacturing or COTS
Ground Control Station		
Command and Control Module	UAV control electronics	COTS or FPGA
Human Machine Interface	UAV control electronics	COTS or FPGA
Communication Module	Specialized electronics	COTS or FPGA
Power Module	Power modules	COTS, possible additive manufacturing
Provide Other Support Functions (Launch and Recovery)	Mechanical modules	Additive manufacturing

The discussion on realizing the building blocks will take place in three sections, with each section addressing the approach for realizing the following:

- development of the UAV structures and control surfaces through additive manufacturing
- options implementing the specialized electronics modules through the use of commercial-off-the-shelf (COTS) items
- options for the development of special to type control modules (predominantly the electronics) for the UAV through the use of field programmable gate arrays (FPGAs)

A. SECTION 1—ADDITIVE MANUFACTURING AS BUILDING BLOCKS FOR UAV STRUCTURES AND CONTROL SURFACES

Additive manufacturing is also known as three-dimensional (3D) printing. The term is coined because materials are printed layer-by-layer into devices as opposed to the traditional subtractive manufacturing approach.

Since the 1980s, more than 30,000 patent applications relating to 3D printing were filed, all cutting across many technology areas (IPO 2013, 46). While the technology itself is not new, the systems and processes that enable 3D printing have undergone substantial improvement over the time frame. 3D printing technology has advanced from its use for prototyping to the manufacturing of end-use products (IPO 2013, 46).

With additive manufacturing, complexity in design could be realized without the hefty "costs associated with traditional manufacturing, such as tooling, fixtures and the need for assembly" (Freebody 2015, 40). Additionally, "design changes and iterations are hassle-free with the added advantage that time to market can be shortened for new or updated products" (Freebody 2015, 40). Additive manufacturing has also enabled production in lower volumes that may not have been cost-beneficial using the traditional approach to manufacturing (Government Accountability Office [GAO] 2015, 7). It is also capable of producing complex geometric features that are hard to realize otherwise (GAO 2015, 21).

The aviation and aerospace industries have utilized the "technology—which is ideal for producing cost-effective out-of-production spare parts on demand" —to address their spare part needs (Freebody 2015, 40). The approach eliminates the cost associated with tooling and molds for manufacturing while providing "opportunities for inexpensive redesign as needs and demands iterate and change" (Freebody 2015, 40–44).

In 2014, a tool was printed using a 3D printer in the ISS. In the demonstration, a design file was transmitted from the earth to the ISS. The tool was a ratchet wrench that took less than a week from being designed to being built, including the approval by relevant safety authorities and NASA reviewers before the design was sent to space and printed by the 3D printer in four hours (see Figure 12. NASA's experience demonstrated the "enormous potential for building tailor-made tools for any unexpected repairs" or requirements, "providing a greater degree of autonomy and flexibility to the astronauts" as well as paving the way ahead for innovative manufacturing techniques that could revolutionize capability induction (Freebody 2015, 41).

Figure 12. Ratchet Wrench Printed in the International Space Station.
Source: Harbaugh (2015).

In a separate effort, the European Space Agency (ESA) is also working in collaboration with 3D Systems to investigate the current state of metal additive manufacturing/direct metal printing (DMP) to assess its potential and maturity in light of future engine development. As part of the investigation, 3D Systems produced three critical engine parts (injectors, combustion chambers and expansion nozzles) through the use of DMP with the ESA On Demands Parts Manufacturing Services team. In the investigation, 3D systems produced the expansion nozzle in titanium Ti6Al4V, which meets the mechanical and thermal requirements for the expansion nozzle. Importantly, the state of the current development demonstrates the wide array of possibilities that open up many design and manufacturing options (3DSystems 2016b).

Additive manufacturing systems or 3D printers can now be employed to print the structures of the UAV. The UAV can be printed as and when required from the library of

stereolithographic files or any relevant 3D computer aided design (CAD) files, where the desired type of airframe can be loaded to the additive manufacturing system to be "printed."

With additive manufacturing, "products with moving parts can be printed such that the pieces are already assembled" (Thomas and Gilbert 2014, 1). The SLA-1 was introduced by 3D Systems as the first additive manufacturing system. Since then, there has been increasing proliferation of additive manufacturing systems. The desktop computer and the industrial lasers were other crucial factors that led to the maturity of additive manufacturing (Thomas and Gilbert 2014, 1).

1. Concept of Additive Manufacturing—Layer by Successive Layer

Additive manufacturing is used to refer to the various types of processes used to translate a virtual model into physical models. The "key concept is to slice the design into successive two dimensional (2D) cross-sections that are of finite thickness" (GAO 2015, 5). The 2D sections are then built layer by layer in a successive manner by the additive manufacturing machine to form the physical part. By repeating the process for each 2D section, the geometry of the part is reproduced in the additive manufacturing system. This differs from the normal manufacturing approach where materials are subtracted through drilling, milling or cutting to create a part or product from a larger piece of material. As such, the key difference between the additive manufacturing approach and the normal manufacturing approach is that there is no requirement to adjust for manufacturing processes such as the attention to tooling, use of molds, casts or patterns or other features. This is the basic principles for all additive manufacturing machines, though there are variations in approach and/or techniques used to create the layers of materials and bond them together. Further variations include the speed, types of material used, size, power, layer thickness, accuracy, power requirements, and cost of the additive manufacturing system. An advantage of additive manufacturing is the potential reduction in waste material in the manufacturing process (GAO 2015, 5; Gibson, Rosen and Stucker 2010, v). The contrast between subtractive manufacturing and additive manufacturing, as well as the waste material generated, is shown in Figure 13.

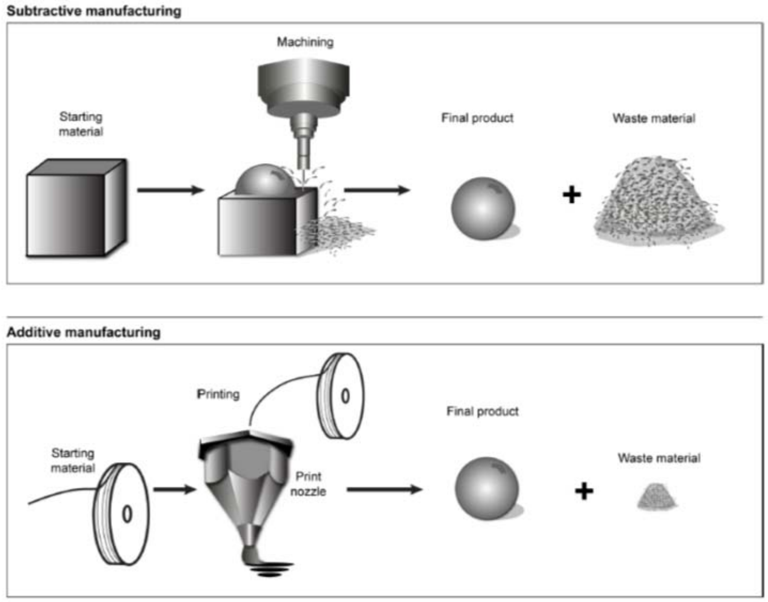


Figure 13. Conceptual Comparison of Subtractive and Additive Manufacturing. Source: GAO (2015, 6).

The key to an additive manufacturing system is the use of a Cartesian printer that moves the thermoplastic extruder (or the print head) along the x, y and/or z-axes to lay down the material that will be fused to become the final 3D object. Following which, the print head is adjusted or elevated using either "threaded rod, or lead screws, to position the z-axis with even greater precision" (Evans 2012, 2–3). Once the desired level along the z-axis is reached, the next layer is printed. Repeating the process over and over again, successive layers are built up and the 3D object is thus printed (Evans 2012, 2–3). To achieve better precision and/or accuracy, stepper motors could be used to implement the movement of the print head. An example of the additive manufacturing system is shown in Figure 14.

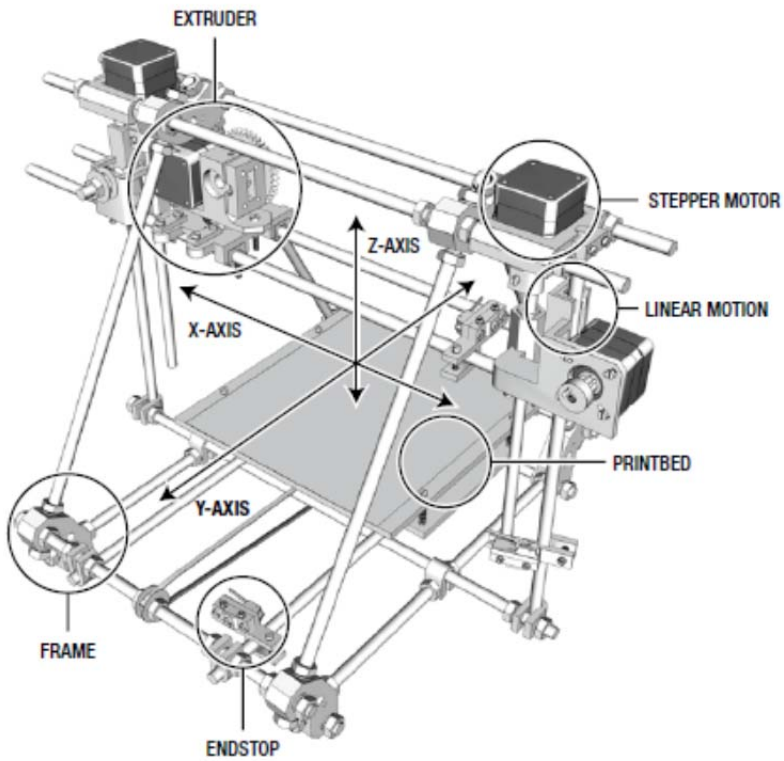


Figure 14. 3D Printer Using Cartesian Systems. Source: Evans (2012, 2).

The mechanical means of moving the print head limit the process speed in two ways: the speed of the print head, and the speed at which the materials are melted and fused together. As such, the latest implementations of 3D printer use photonics or lasers and an arrangement of mirrors and prisms to direct the photon to the material on the vat.

2. Generalized Process Chain for Additive Manufacturing

Having covered the broad concept of additive manufacturing, the generalized process chain for additive manufacturing will be discussed. See Figure 15.

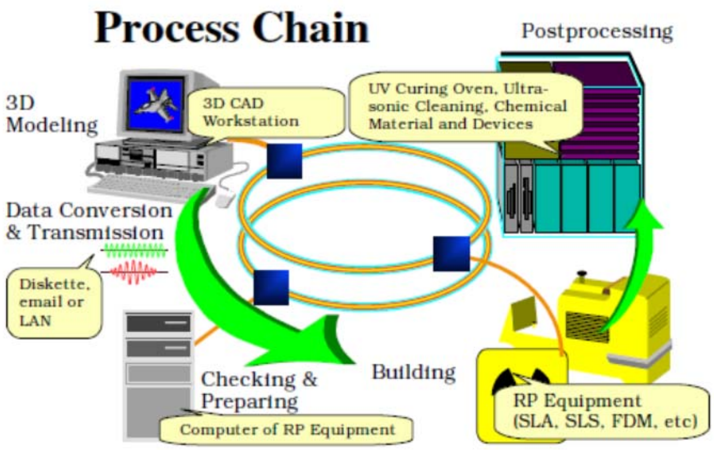


Figure 15. Process Chain for Additive Manufacturing. Source: Chua, Leong, and Lim (2003, 26).

"There are a total of five steps in the process chain" to translate from "file to form." "These are 3D modeling, data conversion and transmission, checking and preparing, building and post-processing" (Chua, Leong, Lim 2003, 26).

a. 3D Geometric Modeling

The designer uses 3D computer aided design (CAD) to generate a model of the part (Gibson 2002, 8). The software representation for a 3D geometric model is encapsulated in the STL output file format. The format originates from 3D Systems, which pioneers the **ST**ereo**L**ithography system. "The STL file format approximates the surfaces of the model using tiny triangles to describe the surfaces to be built. Each triangle is described as three points with a facet normal vector indicating the outward side of the triangle" (Gibson et al. 2010, 23). For highly curved surfaces, many more triangles will be required (see Figure 16).

Figure 16. (Left) CAD Model, (Right) STL Format. Source: Gibson, Rosen and Stucker (2010, 23).

b. *Data Conversion and Transmission*

Once a computer model is generated for a physical object, it needs to be communicated to the additive manufacturing system for interpretation and thus the printing. The data conversion is the process of converting the CAD file to the format that can be interpreted and thus printed from the additive manufacturing system. The transmission refers to the transfer of the design from the design environment to the location of the additive manufacturing system, where the computer model is printed. The workstation and the additive manufacturing system could be situated in different locations.

With the STL file now available, it will be sent to the additive manufacturing system. An example of the interface between software and system is shown in Figure 17. From the figure, it can be seen that the software can display the estimated time for the print job, the status of the additively manufactured object in real time, the temperature of the extruder or the print head setting, and the temperature of the bed that holds the 3D object.

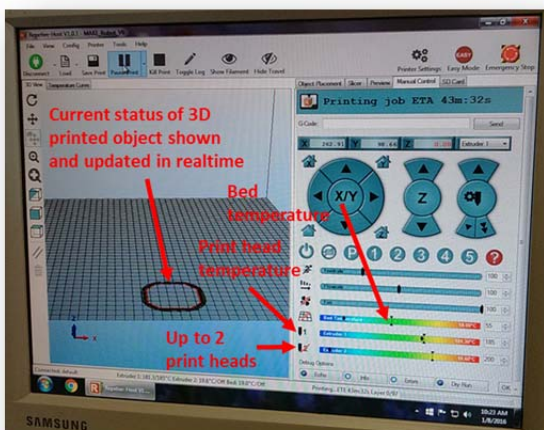


Figure 17. Software Interface with the 3D Printer.

c. *Checking and Preparing*

The next step is checking and preparing. This involves checking the design, as well as the additive manufacturing system, prior to the actual printing. For instance, if “Selective Laser Sintering (SLA) is used to build the part, the orientation of the part is an important factor which

would, amongst other things, influence the quality of the part and the speed of the process" (Gibson 2002, 7–8). For the initial print of the object using STL format, checking also includes verifying the CAD model before the fabrication, as there are drawbacks of the STL format. The drawbacks include redundancy, inaccuracy, and incomplete integrity. These affect the quality of the final build by the additive manufacturing system. Thus, there is a need to visualize, edit, optimize and repair the STL file prior to printing it so as to avoid rework that would result in time and material wastages (Gibson 2002, 7–8). The need for such rework is especially relevant if the 3D model is obtained from the scanning of a physical object using the 3D scanner.

d. *Building*

The building process is where the design is actually printed and takes on a physical shape. For the specific additive manufacturing system, up to two spools of the same or different materials could be used. Thus, there is provision to control up to two print heads. In these instances, it can be seen that only print head one is active. See Figure 18.

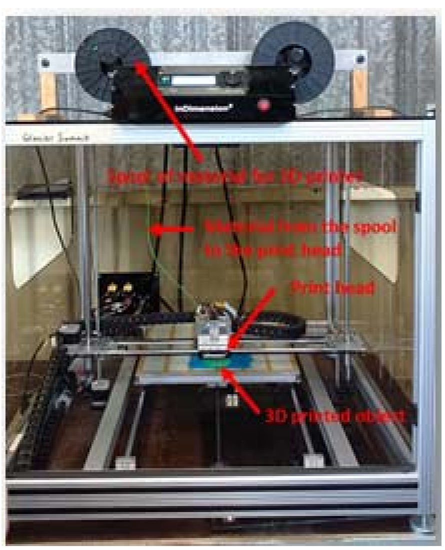


Figure 18. Cartesian Coordinate Additive Manufacturing System Used at Naval Postgraduate School.

e. *Post Processing*

The post-processing task is the final task. The task includes the removal of excess materials and/or parts that may result during the additive manufacturing process. "For parts that

are additively manufactured using the SLA process, the post processing involves the removal of excess resin residing in entrapped portion such as a blind hole of a part as well as the removal of supports" (Chua, Leong and Lim 2003, 43). Figure 19 shows an example of an additively manufactured object. It is a component of the rotor blade to be used in the quadrotor currently studied by NPS.

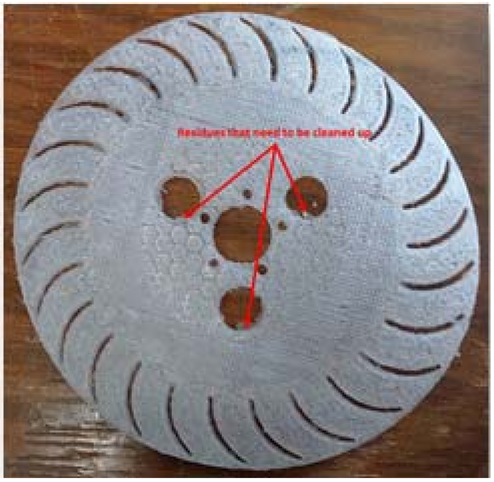


Figure 19. Example of an Additively Manufactured Object.

From Figure 19, it is evident that additional work is required to be carried out at the end of the print job. This includes the cleaning of the residual materials to ensure quality of the print artefacts before the item's actual use. As such, quality check and assurance is another key aspect of the additive manufacturing process that needs to be ensured. Figure 20 shows an imperfect print job where strays of carbon fiber are seen on the surface of the printed objects.

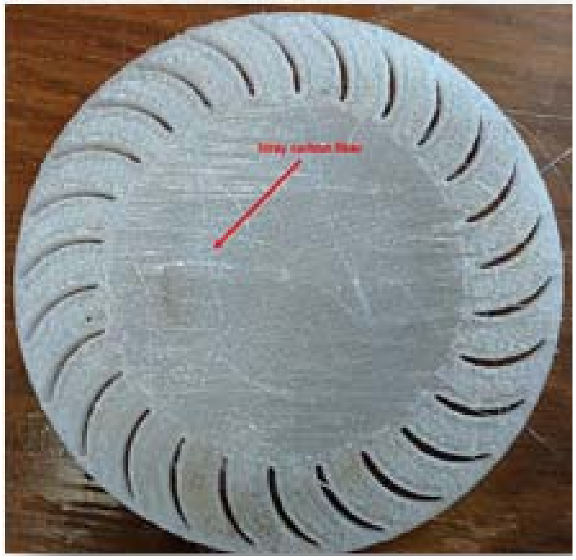


Figure 20. Example of an Imperfect Print Job (with Stray Fiber).

An imperfect additively manufactured object as shown in Figure 20 could arise from a variety of factors. The factors could include a clog or dirty extruder that prevents the proper deposition of the material by the extruder head or an incorrect temperature setting. The latter situation could arise when the extruder head extrudes and deposits the material at position X, and then continues to position Y for another extrusion with no print between positions X and Y. Under this situation, if the temperature of the extruder head setting is not correct or the extruder head is clogged, the filament of the material deposited at position X will traverse between position X and Y, thus creating the situation shown in Figure 20 where stray fibers are not fused to the printed object. This compromises the required material strength and thus the structural integrity of the additively manufactured object.

3. Additive Manufacturing Technologies

Although the additive manufacturing systems employ a layer-by-layer approach to print a 3D object, the techniques and materials used could be different using different technologies for additive manufacturing. The various technologies for additive manufacturing are summarized in Table 10.

Table 10. Additive Manufacturing Technologies.

Additive Manufacturing Technology	Description
Stereolithographic apparatus (SLA); is also known as photo-solidification, optical fabrication.	SLA typically uses photo-polymerization to produce a solid form from liquid. Through the CAD design, the ultraviolet (UV) laser is used to focus on the photopolymer resin to draw out the 3D objects onto the surface of the photopolymer vat. Once the UV laser completes the "drawing" of one layer, the vat is lowered and the photopolymer resin is coated over it where the UV laser continues to "draw" out the next layer. This is repeated until the 3D object is printed.
Fused deposition modeling (FDM)	In FDM, the 3D part is produced by extruding thermoplastic materials that are melted to a semi-liquid state. It is then extruded and hardened immediately to form layers. In FDM, the extrusion nozzle will heat the material, turning the flow of material on or off where the materials are extruded according to computer-controlled paths.
Electron beam melting (EBM)	EBM uses high energy electrons in the form of a focused beam to melt metal powder. This is performed in successive layers in a high-vacuum environment.
Layered object manufacturing (LOM)	In LOM, layers of adhesive-coated materials such as metal, paper or plastic laminates are glued together in a successive manner. The contour of the layer is then cut using CO2 laser. Using this technique, each layer could contain the cross-sections of one or many parts, thereby allowing multiple builds to be conducted at one go. Each successive layer is then laminated and built directly on top of the previous laser-cut layer (Chua et al. 2003, 118).
Selective laser sintering (SLS)	In SLS, a laser is used to sinter powdered material. The material may be small particles of plastic, glass, or ceramics. To fuse the material together, the laser is aimed at the points in a 3D space defined by the design model. With this, the material could be fused to realize a solid 3D object.
Selective laser melting (SLM)	SLM's concept is similar to the SLS's approach. The material is fully melted, however, as opposed to being sintered in SLM. With such an approach, the SLM could be used to create complex objects.

Since the material in each layer are selectively solidified or joined in an additive manufacturing process, the processes thus specify the mechanism for the material transformation (e.g., from liquid form to solid form through either curing or heating). For heating, if a laser is used, then "the requirement is for the laser to carry sufficient thermal energy to cut through a

layer of solid material, to cause powder to melt, or to cause sheets of materials to fuse. For powder processes, the key is to melt the material in a controlled fashion without creating too great a build-up of heat such that when the laser energy is removed, the molten material is able to rapidly solidify" (Gibson et al. 2010, 24).

While there are various processes using different materials that offer a wide range of possibilities, the use will need to be context specific. For instance, if photopolymers are used and a laser beam is used to fuse the material at the specific spot that is held together by the vat, then there is the need to consider the effect of the powder and/or photopolymers shifting around in the powder bed or the vat, respectively, if the host platform that the additive manufacturing system is installed on is non-stationary (e.g., when onboard ship).

Thus, there are pros and cons of each of the additive manufacturing technologies that need to be considered for the DPO through additive manufacturing of UAVs onboard ship. Another consideration is the post processing. Post processing is an important consideration as manual operations are inevitable. While it may not be critical if the object to be printed is not time sensitive, the application onboard ship may be time sensitive and the amount of manpower to perform the post processing may be limited. As example for the SLA printed parts, the post processing involves the removal of "excess resin residing in entrapped portion such as a blind hole of a part, as well as the removal of supports" (Chua et al. 2003, 59). This is similar for the case of SLS parts where excess powder need to be removed. Table 12 shows the post-processing tasks for different additive manufacturing approaches. Evidently, the SLA approach requires the highest number of post-processing tasks. This is an area to note for the implementation of additive manufacturing onboard ship.

Table 11. Post-Processing Tasks for Different Additive Manufacturing Approaches. Adapted from Chua et al. (2003, 59).

	Additive Manufacturing Approach			
Post processing tasks	**SLS**	**SLA**	**FDM**	**LOM**
Cleaning	Yes	Yes	No	Yes
Post curing	No	Yes	No	No
Finishing	Yes	Yes	Yes	Yes

4. Additive Manufacturing Systems—Process and Materials

Although there are a variety of technologies for additive manufacturing as summarized in Table 10, there are also different materials and processes that are employed. According to the 2015 U.S. GAO report, which referenced the 2012 ASTM International (formerly known as the American Society for Testing and Materials), there are seven categories of additive manufacturing processes to group the different types of technologies (GAO2015, 8). They are shown in Table 12.

Table 12. Types of Additive Manufacturing Processes. Adapted from GAO (2015, 6), Thomas and Gilbert (2014, 5).

Process Name	Description
Binder jetting	A liquid bonding agent is selectively deposited to join the powder materials.
Directed energy deposition	Focused thermal energy, such as a laser, is used to fuse materials by melting as the materials are being deposited to form an object.
Material extrusion	Materials are heated and selectively dispensed through a nozzle.
Material jetting	Materials, such as photopolymers or wax, are selectively dispensed through a nozzle.
Powder bed fusion	Thermal energy selectively fuses regions of a powder bed.
Sheet lamination	Sheets of materials are cut and stacked to form an object.
Vat photo-polymerization	The use of certain types of UV light, such as ultraviolet light, to selectively solidify liquid photopolymers.

Beside the processes, there are also different types of materials, of which there are eight categories (Thomas and Gilbert 2014, 6):

- polymers and polymer blends
- composites
- metals
- graded/hybrid metals
- ceramics
- investment casting patterns
- sand molds and cores

- paper

a. Additive Manufacturing Process and Material Combinations

The combinations of the additive manufacturing processes and the materials are summarized in Table 13. It is noted that certain processes are suitable for certain materials.

Table 13. Additive Manufacturing Process and Material Combinations. Source: Wohlers (2012).

	Material extrusion	Material jetting	Binder jetting	Vat photopoly-merization	Sheet lamination	Power bed fusion	Directed energy deposition
Polymers and polymer blends	X	X	X	X	X	X	
Composites		X	X	X		X	
Metals		X	X		X	X	X
Graded/hybrid metals					X		X
Ceramics			X	X		X	
Investment casting patterns		X	X	X		X	
Sand molds and cores	X		X			X	
Paper					X		

b. Additive Manufacturing Systems on the Market

Having now covered the concept, additive manufacturing technologies and process and material combination, the next aspect is the actual type of additive manufacturing system currently available, as well as the future trajectory. Additive manufacturing has continued to mature since its inception. Table 14 provides a snapshot of the latest additive manufacturing system. The key difference between the additive manufacturing technology in its nascent years and now is the range of materials that can now be additively manufactured, and the capability to perform multi-material combination using one common additive manufacturing system. This includes:

- Hybrid manufacturing. Where additive and subtractive work flows are merged, enabling an extension of the scope of products being developed (Freebody 2015, 42).

- Direct metal printing. This is one of the latest developments and provides the capability “to manufacture highly complex, precision components in fully dense metals” (Freebody 2015, 43). This allows designers and engineers “to utilize 3D printing to create metal parts with intricate, internal structures” that would be difficult if not impossible to manufacture any other way (Freebody 2015, 43).

Table 14 provides an illustration on the latest additive manufacturing system printers that are now available in Europe and the United States. The state of the technology is such that direct printing of metal using fine metal powder is now possible, and it can reach a resolution of 15 µm. From 3D Systems, the technology not only exists to be able to perform additive manufacturing of up to 1200 different materials but also to perform it rapidly.

Table 14. Examples Of The Latest 3D Printers Introduced In 2015/6.

Company	Technique	3D Printers and the Models
Concept Laser GmbH	Fusing of powder materials using laser “cusing” process. The melting process generates complex parts, layer by layer, using 3D CAD data with layer thickness between 15 and 150 µm. In the process, metal in fine powder form is melted locally using high-energy lasers where the material solidifies after it cools down. The construction of the metal parts is thus carried out by lowering the build plate, adding new powder, and melting again (Concept Laser 2015). The powder materials could be of: - stainless steel - cobalt-chromium alloy - nickel-based alloys - reactive powder materials (such as aluminum and titanium alloys) - precious metals (such as gold or silver alloys). (Freebody 2015, 44)	X line 2000 R using single or dual 1kW laser. Build volume: up to 31.5” x 16” x 20.” Printer is built with serial production in mind and is optimized for continuous operation of a delicate material. M2 cusing using single or dual 200 or 400W laser. Build volume: 10” x 10” x 11.” M1 cusing using single or dual 200 or 400W laser. Build volume: 10” x 10” x 10.” Mlab cusing R using 100W laser. Build volume: 3.5” x 3.5” x 3.” Mlab cusing using 100W laser. Build volume: 3.5” x 3.5” x 3.” Printer is intended for use with non-reactive materials (Concept Laser 2015).
3D Systems	The current generation of 3D printer from 3D Systems is capable of printing more than 1200 materials.	ProX DMP 320—designed for high-precision and high-throughput direct metal printing such as the printing of

Company	Technique	3D Printers and the Models
	The materials could range from heat-resistant nylons to flexible elastomers to stainless steel to biocompatible materials (Freebody 2015, 44).	complex objects using titanium, nickel super alloy parts or stainless steel. The printer offers a 275mm x 275mm x 420mm build volume. (3DSystems 2016a) The MJP 3600 series is another printer that is designed for both high capacity and resolution with printing at fast speed. The MJP5500x, on the other hand, has been designed to be capable of printing using multiple materials (3DSystems 2015).

Given the current state of technology, the interest in and the trajectory of additive manufacturing systems, it can be concluded that in-situ manufacturing of parts for UAVs is a tenable approach.

5. Types of Additive Manufacturing System

Having covered the available additive manufacturing techniques and processes, the next step is to identify the type of additive manufacturing system that could be used for shipboard additive manufacturing. Given the diversity of additive manufacturing systems available to individual use and high-end manufacturing, there is a need to discern the requirements of the systems through identification of the key attributes to identify what is feasible and the possible risks. As such, the following discusses the attributes of the additive manufacturing systems before the macro assessment of the additive manufacturing system.

a. Attributes of Additive Manufacturing System

Build Preparation. The build preparation shall be able to be executed from any workstation on the network with a software that allows full automation to enable ease of job setup and submission. Such automation should include the feature to perform automated part placement and the automatic generation of support structures when the items are printed (3DSystems 2014, 10).

Part Cost. Part cost is important in the total cost of ownership consideration. It is typically expressed in cost per volume but could be dependent on the materials used and technologies employed. The ability to minimize waste through recycling or re-use of materials is a potential area to be considered. For instance, technologies using powder-based approaches could enable the recycling of unused material, thus resulting in less waste (3DSystems 2014, 10).

Print Capacity. The print capacity is important as it determines the size of the item that could be printed or the number of items that could be printed concurrently. It thus relates to the print volume (3DSystems 2014, 15).

Resolution. This is important in assessing the types of parts that could be additively manufactured. An example is machine parts where the print resolution could affect the surface properties, which in turn affects the overall performance of the parts when integrated to the UAV. Resolution could be expressed in "dots per inch (DPI), Z-layer thickness, pixel size, beam spot size, bead diameter" (3DSystems 2014, 12). It is therefore important that a similar metric be used when comparing different 3D printers, though there might be different metrics used by different manufacturers (3DSystems 2014, 12).

Accuracy. With additive manufacturing, the parts are produced layer by layer. The process may thus generate additional variables, such as material shrinkages, which should be considered and compensated as part of the print process to achieve the desired accuracy. It is therefore a key attribute to compare against the available additive manufacturing system. According to 3DSystems, "powder-based 3D printers using binders typically have the least shrink distortion attributable to the print process and are generally highly accurate whereas additive manufacturing technologies with plastic which typically use heat and/or UV light as energy sources to process the print materials could add variables that can impact accuracy" (3DSystems 2014, 12).

Material Property. The needed material characteristics are important in determining and hence selecting the most applicable additive manufacturing system. This is because there are strengths and weaknesses associated with each technology that need to be considered. Such considerations include the material strength as well as stability of parts over time and across various operating environments (3DSystems 2014, 15).

Power Requirements. Power is required for additive manufacturing processes as well as operating the end product. The focus is on the additive manufacturing process. Depending on the specific technique or deposition processes and the type of heating used for the additive manufacturing systems, the power requirements will vary. The power requirement will be different if a plastic is being heated and fused using laser as compared to metallic powder energized and fused using electron beam. As such, the power requirement may vary from "several hundred watts for lasers working with polymer materials to several kilowatts for electron beam systems" (NAS 2014, 46). Table 15 shows the energy consumption of five additive manufacturing materials.

Table 15. Energy Consumption Of Five Additive Manufacturing Materials. Source: NAS (2014, 46).

Process	Material	Average Power (kW)	Energy Consumption (kWh/kg)
Stereo-lithography	Photopolymer	0.88	20.7–41.4
Selective laser sintering	Polyamide and typically other semi-crystalline thermoplastic polymers	0.3	29.8–40.1
Fused deposition modeling	ABS, PLA, polycarbonate and typically other amorphous thermoplastic polymers	1.3	23.1–346
Selective laser melting	Stainless steel, SAE316L	0.4	31
Electron beam melting	Titanium, Ti-6Al-4V	3	17

From Table 15, it is assessed that the power requirements and energy consumption could be fulfilled by a ship's power supply. Nonetheless, the circuit breakers and electrical distribution network will need to be sized up to be able to cater to the most demanding process using fused deposition modeling, which could consume up to 346 kWh per kg of 3D object printed (NAS 2014, 46).

Speed. The speed that the additive manufacturing systems could print an object is an important consideration that may limit their overall effectiveness for shipboard additive manufacturing. It includes:

Complexity of design. A complex structure may require additional support structure such as the use of scaffolding to support the build. The scaffolding may thus require additional space for the print head to traverse, thus affecting the overall print speed. This may, however, be eliminated or minimized with the careful orientation of the design for the build. If the software does not optimize this for the user, then this may be a variability that will affect the speed of the build. On the other hand, the use of FDM may not require the use of support structure as only the physical structure is being fused by the laser, while the raw material (e.g., the metal powder) may continue to remain on the vat.

Total processing time. The additively manufactured items may include post-processing tasks such as the cleaning (e.g., removal of the support structure), post curing and finishing. As such, the speed of the additively manufactured systems should be assessed using the total processing time, in addition to the actual build time. On the other hand, there is a need to assess the operator's competency in their knowledge, skillsets and abilities in performing the post-processing tasks. As such, the operator's competency is another variable that will affect the total processing time.

Types of raw material use. Different builds require the use of different raw materials. The materials have different characteristics, such as the melting point (the temperature required to melt and fuse it). To ensure a good build, there is a need to consider changing the print head in order to achieve good adhesion layer upon layer. Given that some printers have upwards of 100 possible different materials, it is expected that there will be a wide variability in the print speed of a particular build.

b. Commercially Available Additive Manufacturing System

There are many different models of additive manufacturing systems. The following provides the range of additive manufacturing systems that could be considered for shipboard uses. These include polyjet printers using photopolymers, as well as printers using fused deposition method (FDM). Table 16 shows the 3D printer using photopolymer material. Six possible models are shown with different build size, print resolution, printing modes, accuracy, and machine dimensions.

Table 16. Comparison of Polyjet's Additive Manufacturing System. Source: 3DPrintersCanada (2011b).

Features	Eden260V	Eden350V	Eden500V	260 Connex	Connex 350	Connex 500
						
Layer thickness	28-micron	16-micron	16-micron	16-micron	16-micron	16-micron
Build tray size (X*Y*Z)	260 x 260 x 200mm	350 x 350 x 200mm	500 x 400 x 200mm	260 x 260 x 200mm	350 x 350 x 200mm	500 x 400 x 200mm
Net build size	255 x 252 x 200mm	340 x 340 x 200mm	490 x 390 x 200mm	255 x 252 x 200mm	342 x 342 x 200mm	490 x 390 x 200mm
Print resolution (DPI)	X-Axis 600 Y-Axis 600 Z-Axis 1600	X-Axis 600 Y-Axis 600 Z-Axis 1600	X-Axis 600 Y-Axis 600 Z-Axis 1600	X-Axis 600 Y-Axis 600 Z-Axis 1600	X-Axis 600 Y-Axis 600 Z-Axis 1600	X-Axis 600 Y-Axis 600 Z-Axis 1600
Printing modes	2 modes	2 modes	2 modes	3 modes	3 modes	3 modes
Accuracy	0.1—0.2mm	0.1—0.3mm	0.1—0.3mm	0.1—0.3mm	0.1—0.3mm	0.1—0.3mm
Machine dimension	W 870mm D 735mm H 120mm	W 1320mm D 990mm H 1200mm	W 1320mm D 990mm H 1200mm	W 870mm D 735mm H 1200mm	W 1420mm D 1120mm H 1130mm	W 1420mm D 1120mm H 1130mm
Weight	280kg	410kg	410kg	264kg	500kg	500kg
Other comments				Multi-material	Multi-material	Multi-material

The printers highlighted in Table 16 use the STL format. The material used for the additive manufacturing is in cartridge form with up to 3.6 kg per cartridge of photopolymer. The operational environment is suitable for temperatures of 18ºC to 25ºC with relative humidity of 30–70%. The print resolution of 600 dpi and 1600 dpi is translated to 42μm and 16μm, respectively. The choice of printers offers either high-speed or high-quality print. Additionally, 260 Connex, Connex 350 and Connex 500 offer the capability of having multiple materials being built together, thus offering the use of composite materials in creating the final product (3D Printers Canada 2011).

From the table, it can be seen that the printer could easily be installed and used onboard a ship. The net build size, however, suggests that if a larger end product is required, there is a need to be able to integrate the various printed items together. For example, if a UAV wing is to be printed, the wing could be printed in various parts. The finished product is connected together. Table 17 shows the additive manufacturing system using the fused deposition method.

Table 17. Comparison of FDM Printer. Source: 3DPrintersCanada (2011b).

Features	**Dimension 1200es**	**Dimension Elite**	**Fortus 250mc**	**Fortus 360mc**	**Fortus 400mc**	**Fortus 900mc**
						
Build Size	254 x 254 x 205mm	203 x 203 x 305mm	254 x 254 x 305mm	355 x 254 x 254mm	355 x 254 x 254mm	914 x 610 x 914mm
Layer Thickness	0.254mm or 0.33mm	0.178mm or 0.254mm	Multiple build speed options for fine feature detail and smoother surface finish 0.330mm 0.254mm 0.178mm	Multiple build speed options for fine feature detail and smoother surface finish 0.330mm 0.254mm 0.178mm 0.127mm	Multiple build speed options for fine feature detail and smoother surface finish 0.330mm 0.254mm 0.178mm 0.127mm	0.330mm 0.254mm 0.178mm
Accuracy	Not available	Not available	Parts are produced within an accuracy of ± 0.241mm	Parts are produced within an accuracy of ± 0.241mm	Parts are produced within an accuracy of ± 0.241mm	Parts are produced within an accuracy of ± 0.241mm.

From Table 17, it can be seen that the Fortus series offers multiple build speed options with choices of the finishes/details of the end product. With respect to build size, Fortus900mc offers one of the largest build sizes, which would be useful for producing large individual 3D parts or high-volume production runs of many small 3D parts. With the print accuracy, layer thickness and build size, it is a suitable candidate for use in the printing for unmanned systems components. For the Fortus 900mc, multiple materials (with multiple colors) could be used. It includes the use of (a) ABS-M30 for trying out ideas; (b) ABS-M30i, which is a biocompatible 3D printing material; (c) ABS-ESD7 (static dissipative thermoplastic) for use where static charge could damage components and impair performance; (d) FDM Nylon 12, which could be used to create items for applications that demand high fatigue resistance; (e) PC-ABS for items that require superior impact strength; (f) PPSF for items that are required to withstand punishing heat and exposure to chemicals; and (g) ULTEM 9085, which is a thermoplastic that possesses well-rounded thermal, mechanical and chemical properties (3D Printers Canada 2011a).

6. Assessment of Additive Manufacturing System for Shipboard Use

The discussion on additive manufacturing systems is necessary to assess the feasibility for shipboard use. While the discussion indicates that additive manufacturing could enable a new approach to manufacturing, there has been no information on its use onboard ship.

The specifications for additive manufacturing systems do not provide information on the permissible operating environment such as the permissible roll, pitch and yaw in m/sec, as there is no consideration to have the additive manufacturing installed onboard a non-stable platform (i.e., the ship). As such, it is assessed that the additive manufacturing system using laser fusion may not be suitable for shipboard use unless it can be stabilized or unless the ship is a stable platform operating in low sea-state condition. This is because the photopolymer or the metal powder may not be of uniform thickness due to the motion of the ship. The implication is that when the laser "shines" on it to fuse with the previous layer, the result is non-uniform, thereby affecting the quality of the final build. It is further postulated that the factors affecting the result of the additive manufacturing process could be affected by

1. the type of materials and hence the associated curing time
2. the deposition technique
3. the environment (sea state)
4. the type of naval platform (larger platforms with stabilizers systems would experience less roll in higher sea-states and smaller platforms without stabilizing systems would be more prone to roll in higher sea states.)

Nonetheless, there are currently no data available to suggest that the highlighted factors of (1) types of material, (2) environment (such as humidity and ship's movement) and (3) types of naval platform would place a constraint on or impact the additive manufacturing process.

Finally, there may not be a one-size-fits-all additive manufacturing system that is the most suitable. As such, there could be a need to acquire more than one additive manufacturing system for the purpose of simultaneous building as well as to take advantage of the combination of having different material properties for a system to be implemented. Such selection must be cognizant of the intended use and, concomitantly, the desired attributes of the end product. If

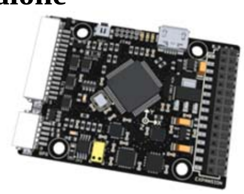
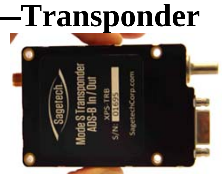
space onboard ship is a constraint, however, then there is also a constraint on the size of the additive manufacturing system that could be installed onboard ship.

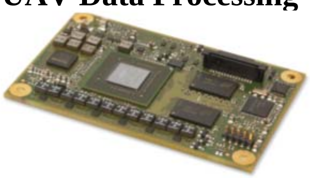
B. SECTION 2—COMMERCIAL-OFF-THE-SHELF AS BUILDING BLOCK FOR SPECIALIZED ELECTRONIC MODULES

In Chapter II, it was highlighted that specialized modules are required to implement the functions for the UAV. Such functions could not possibly be additively manufactured. For example, it includes the communication module to implement the communication link with the GCS, the navigation of the UAV using the inertial navigation systems (INS) and/or the global positioning system (GPS) by the navigation module, and the payload module (which could include the infra-red camera, synthetic aperture radar and/or explosive). These modules may be implemented as commercially-off-the-shelf (COTS) items, with a wide range of costs, interface requirements and performance specifications, though they may not be designed for use with the UAV in mind. The selection of the appropriate COTS items for implementation would need to be sensitive to the performance specifications. The performance specifications include the size, weight, power requirements and/or resolutions that may be used for the UAV under consideration. Diversity in range of possibilities for a single implementation of a certain module (e.g., choices of INS or GPS for the navigation module) will be very useful to expand the repertoire of options for the UAV to be DPO for different contexts and hence different applications. The richness of the options available through COTS would thus provide the additional flexibility for the DPO of UAV.

Table 18 provides a compilation of what is currently available for the implementation of the specialized function. The intent is to provide an illustration on the range of feasibility and not a comprehensive catalogue of the items. As such, the table is a subset to the full range of possibilities that are evolving with the demands of the consumer and the technological market.

Table 18. Specialized Electronics Modules—Implementation Using COTS.

Functions to be undertaken	Items Specifications
UAV—Navigation  Source: Advanced Navigation (2015)	**Advanced Navigation—Spatial FOG Dual** "A ruggedized GPS-aided inertial navigation system that provides accurate position, velocity, acceleration and orientation" (Advanced Navigation 2015). Spatial FOG Dual utilizes "ultra-high accuracy fiber optic gyroscopes, accelerometers, magnetometers and a pressure sensor with a dual antenna real time kinematic (RTK) GNSS receiver to achieve the navigation function" (Advanced Navigation 2015).
UAV—Autopilot and Flight Management Unit Standalone  **Stacked Operation**  Source: Measurement Specialties (2012)	**PX4FMU Autopilot/Flight Management Unit** Autopilot-on-module "for fixed wing, multi rotors, helicopters, cars, boats and any other robotic platform" (Measurement Specialties 2012). The system enables a stacking approach for combining the PX4FMU autopilot-on-module with a carrier board that interfaces with the platform to allow customized solutions for different vehicles while still sharing the same autopilot module (Measurement Specialties 2012).
UAV—Transponder  Source: Sagetech (2016)	**Sagetech—Transponders** The transponders enable the UAVs to be recognized and managed by forward air controllers and Air Traffic Control (Sagetech 2016).
UAV—Synthetic aperture radar  Source: IMSAR (2015)	**IMSAR's NSP-3 NanoSAR** Ku-band NanoSAR system for "SAR imaging, coherent change detection (CCD), moving target indication (MTI), and maritime search and detection" (IMSAR 2015) **Size**: 3.75" x 30.5" **Weight**: 7 lbs **Power**: 60W **Specifications**

Functions to be undertaken	Items Specifications
	- Range resolution: 0.1, 0.3, 0.5, 1, 2, 5, 10m - Maritime detection range: 12.5km - GMTI: 7+km - SAR imaging range: 22km (at 1m resolution) - Frequency: KU band (IMSAR 2015)
UAV—Aerial Cameras  Source: Phaseone Industrial (2013)	**PHASEONE Industrial—Aerial Cameras** Medium-format camera systems for aerial photography. Camera weight starts at 1.3kg with an 80mm lens (Phaseone Industrial 2013).
UAV Data Processing  Source: Abaco Systems (2016)	**Abaco—mCOM10-K1** General purpose computing on graphics processing units (GPGPU) for data-intensive applications. Used for parallel processing of data-intensive applications, particularly in video and image processing, radar, sonar, medical and transportation. Specification Size: 84 x 85mm I/O: Audio, Gigabit Ethernet, GPIO, HDMI or DV1, SATA, Serial, USB (Abaco Systems 2016)
GCS—Communication  Source: IMSAR (2015)	**IMSAR's Viper LS** "Communications base station with an integrated L & S band communication link" (IMSAR 2015). **Size**: 2.965" x 2.415" x 7" **Weight**: 70 lbs **Power**: 24V DC **Specifications** - RF output power: ~1W - Range: 120km - Data rate: 466kbps—6.4Mbps - Beamwidth: 7.5˚(min)—10˚ (max) - Antenna pointing accuracy: <0.3˚ - Supply voltage: +24V DC - Weight: 70 lbs (IMSAR 2015)

In addition to the above, the consideration for the use of COTS product includes the fact that the firmware should have reached a level of maturity with regards to its reliability and usability. The matured COTS products are readily available and instructions are in place for implementation. There could be situations, however, where COTS can be hard to integrate with other components and/or subsystems for the UAV if its codes are meant for the use of the product itself and its functions may not accommodate that required by the unmanned systems.

The use of COTS enabled the implementation of different UAVs (e.g., STOL, HTOL or hybrid, with different performance characteristics) using common items. These enable the ship to carry a common stock of COTS and raw materials and implement different UAVs using the DPO concept. Contrast this with the need to be equipped with different UAVs for the foreseeable mission that might restrict its operational flexibility if the UAV is defective or limited in performance.

C. SECTION 3—FIELD PROGRAMMABLE GATE ARRAYS AS BUILDING BLOCKS FOR UAV CONTROL ELECTRONICS

This section discusses the building blocks for UAV control electronics that cannot be fulfilled using additive manufacturing or COTS. The section also explores the maturity of the approach to implement the UAV control electronics for the UAV.

According to Piqué and Chrisey, there is “a huge push for flexible and more rugged systems for the military” (Piqué and Chrisey 2002, 24). They suggested that rapid development will not only reduce the time to develop electronic systems but also improve the capability and wherewithal to “produce components and systems on demand” (Piqué and Chrisey 2002, 24). This could combat against component and system obsolescence yet provide the added benefit of reducing inventory and maintenance costs. They further highlighted that the “long logistics and inventory tail must be reduced” as the military drives toward more expeditionary missions that could involve “decentralized” mission scenarios; this is a situation characterized by the use of mobile and flexible units in lieu of major logistics support or supplies distribution center (Piqué and Chrisey 2002, 24). In their opinion, the use of rapid-prototyping for electronic components and systems through direct-write technologies that enable small-lot manufacturing work could be a possible solution for the military (Piqué and Chrisey 2002, 24).

1. Options for Implementing UAV Control Electronics

The control of the UAV would require a command module. Whereas the sensors, navigational and communication modules are specialized items that can be implemented using COTS items that feature the latest technology, the command module must be able to integrate all the various modules and be custom-configured to the UAV for the specific mission it is expected to undertake. For example, a UAV for ISR mission, UAV as a guided projectile, or UAV for humanitarian assistance and disaster relief operations would all have potentially different command modules due to the different flight and/or mission profiles. In the case of a guided projectile, the command module is implemented to perform terminal homing on an acquired target, whereas the command module for a UAV intended for humanitarian and disaster relief will be implemented to provide the image of the area being scanned back to the GCS.

Based on the functional hierarchy for unmanned systems, the command module is a digital system that can be implemented using many different devices to fulfill the digital logic design. The possible implementation ranges from fixed design to flexible design approaches:

- Direct-write
- Application specific integrated circuit (ASIC)
- Field programmable gate array (FPGA)

2. Direct-Write

Broadly, the direct-write technologies are the equivalent to additive manufacturing for electronic systems. The direct-write is in the micro-meter range and finds particular application in the mesoscale arena; in particular, "electronic devices that straddle the size range between submicron range (microelectronics) to the 10mm-range (surface mount components)" (Piqué and Chrisey 2002, 1, 18). Direct-write refers to the range of technology and techniques "to deposit and pattern different thin-film materials for the fabrication of components and systems such as those found in electronic devices, sensors" (Piqué and Chrisey 2002, 1, 18). Thus, the use of direct-write technologies could be used to implement the command modules so as to "fabricate parts of electronic circuits by methods that occupy a small production footprint, are CAD/CAM

compatible, and can be operated by unskilled personnel or totally controlled from the designer's computer to the working prototype" (Piqué and Chrisey 2002, 1–2). The various techniques for direct-write are shown in Figure 21.

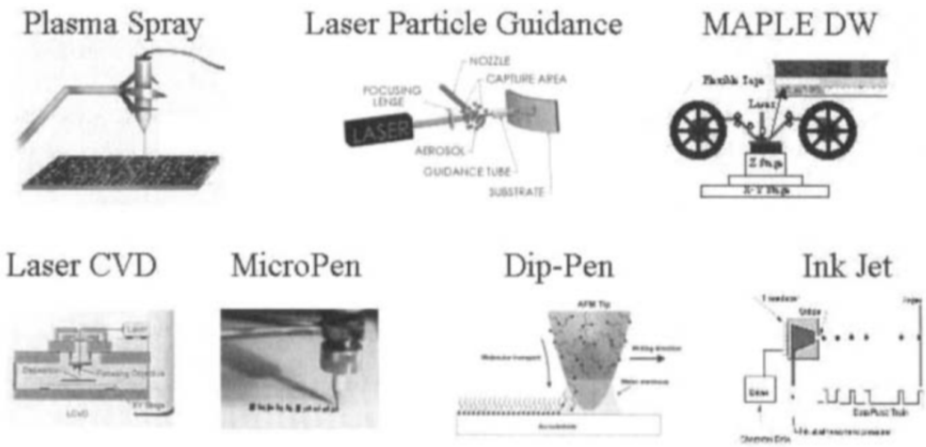


Figure 21. Different Direct-Write Techniques. Source: Piqué and Chrisey (2002, 4).

Figure 21 shows that there is a wide range of techniques available for direct-write. Similar to the additive manufacturing approaches, the techniques differ in how the materials are transferred, deposited or dispensed and the comparison across the techniques used includes "cost, speed, resolution, flexibility to work with different materials, final material properties, as well as processing temperature" (Piqué and Chrisey 2002, 4). The postulated application for the direct-write approach includes a micro-UAV shown in Figure 22. The example illustrates the "ability to combine different materials, devices and power for complete electronic module functionality using direct write" (Piqué and Chrisey 2002, 19).

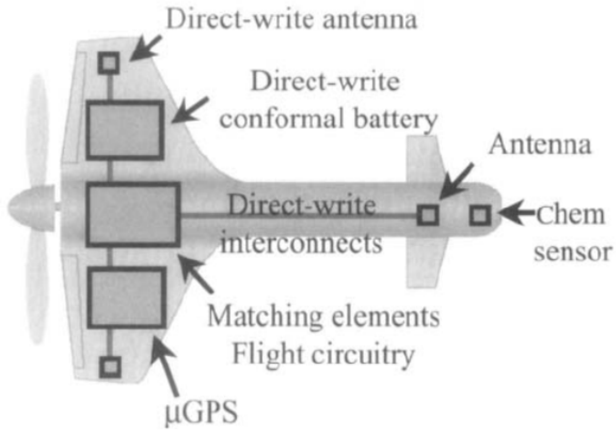


Figure 22. Micro-UAV Using Direct-Write Technique.
Source: Piqué and Chrisey (2002, 4).

The diagram shows the capability of direct-write in implementing a vast array of components that could be developed. It ranges from complete functional circuitry such as the micro-GPS, the chemical sensor, the antenna and the wiring that connects the various modules together. While such approaches hold promise in holding just the raw materials to produce different components to the UAV for different missions, the widespread use may be limited currently as compared to the use of FPGA (discussed later). The primary considerations are the skill sets required to operate, print and validate the printed electronic systems before its actual integration and use onboard the UAV. The key concern is to achieve successful additive manufacturing of the UAV onboard ship, yet minimize training and time spent on manufacturing the UAV. Nonetheless, the use of the direct-write approach could be carried out in a shore facility.

3. Application Specific Integrated Circuit

The flexible design approach could be approached using the application specific integrated circuits (ASICs) or the field programmable gate arrays (FPGAs) whose internal functions and implementation of digital logic are customizable by the user. The difference between ASIC and FPGA is that "ASICs require a final customized manufacturing step for the user-defined function whereas the FPGA requires user programming to perform the desired operation" (Hamblen, Tyson and Furman 2006, 44).

ASIC fabrication requires considerable tooling costs and, in general, is not economical for low-volume manufacturing (Piqué and Chrisey 2002, 261). This is the same observation made by Hamblen et al., who state that "ASICs require custom manufacturing and development, with several months normally required and involve substantial setup with equally substantial cost involved" (Hamblen, Tyson and Furman 2006, 45). In addition to cost, there are also issues of complexity. For ASIC, the full custom approach may involve the use of general and/or special microprocessors and random access memory to fulfill the function. Given the level of involvement for a full custom approach, it is assessed that the approach is more suited for development work at shore and/or research and development facilities as opposed to rapid implementation using DPO onboard ship at sea. As such, while it offers another possibility for the DPO of UAV, it is not further pursued here.

4. Field Programmable Gate Array

Field programmable gate array (FPGA) can be seen as an amalgamation of multiple logic gates or programmable logic elements (LE) on a single chip. Using the LE, different logic gates can be implemented to realize the desired design. The use of the LE can be scaled up by connecting it to the other LE on the same chip through a programmable interconnection network to perform complex operations (Hamblen et al. 2006, 47). Figure 23 shows examples of the FPGAs.

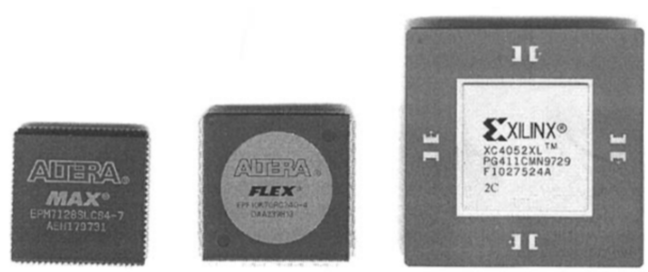


Figure 23. Examples of FPGAs. Source: Hamblen et al. (2006, 47).

With increasing complexity and higher gate densities, it is not uncommon that an individual FPGA can approach beyond 10,000,000 gates, rendering the use of manual design untenable. In its place, hardware description languages (HDLs) as well as logic synthesis tools with their own library of logic elements could be used to assist in FGPA-based design. Logic

synthesis using the HDLs helps to reduce development time and cost while enabling "(1) more exploration of design alternatives, (2) more flexibility to changes in the hardware technology, and (3) promotes design reuse. Examples of such HDL are the VHDL (VHSIC (Very High Speed Integrated Circuit) Hardware Description Language) and Verilog" (Hamblen et al. 2006, 56 and 88).

The typical FPGA CAD design flow using VHDL is shown in Figure 24. After the design is completed in VHDL, it is "automatically translated, optimized, synthesized and saved as a text-based representation of the logic diagram, also known as a netlist." From here, "a functional simulation is typically performed prior to the synthesis step to speed up simulations of large design." Once the design using VHDL is verified, it will be programmed to the device. To do that, "an automatic tool fits the design onto the device by converting the design to use the FPGA's logic elements through device fitting" (Hamblen et al. 2006, 56). It does this by first "placing the design in specific logic element locations in the FPGA before selecting the interconnection routing paths" (Hamblen et al. 2006, 56). Advanced designs that are sensitive to timing constraints between logic elements could be implemented in the FPGA using the optional constraints "to aid the place and route tool in finding a design placement with improved performance" (Hamblen et al. 2006, 56).

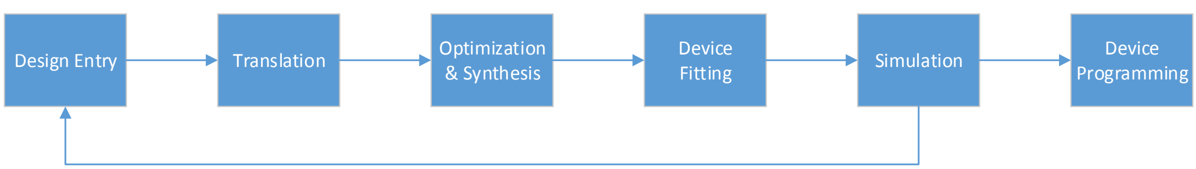


Figure 24. CAD Tool Design Flow for FPGAs. Source: Hamblen et al. (2006, 56).

Newer FPGA CAD tools have integrated the use of "other languages such as C and Java. Some of these programs output VHDL or Verilog models as an intermediate step. Additionally, tools that automatically generate an FPGA design from other engineering tools such as MATLAB-Simulink or LabVIEW" have also been introduced (Hamblen et al. 2006, 57).

With the flexibility in designing FPGAs using common programming software using an established set of libraries, there are increasing uses of FPGA-based designs. These have led to generation of FPGAs with "ten million gates with clock rates at 1GHz and beyond" (Hamblen et

al. 2006, 57). An example application of such FPGAs has been used for single chip replacement for "digital signal processing, image processing, high speed communications and networking equipment such as routers and switches, microprocessors, co-processors, and micro-peripheral controllers" (Hamblen et al. 2006, 57). The use of FPGA has also expanded to include reconfigurable computing where the FPGAs can be rapidly "reprogrammed or reconfigured multiple times during normal operation to enable them to perform different computations at different times for a particular application" (Hamblen et al. 2006, 256).

Comparing direct-write, ASIC and FPGA, it is assessed that FPGA renders itself readily for use onboard ship for the implementation of DPO CONOPS as compared to direct-write and ASIC. For direct-write, the process is tedious and may render itself useful for the development of printed circuit boards, but not the implementation of the digital logic for the command and control modules. On the other hand, the use of ASIC requires time and effort to retool. Thus, direct-write and ASIC would be well-suited for shore use in the detailed research and design phase, whereas FPGA would be well-suited for use onboard ship where the designs are tested and validated in shore-based facilities, then transmitted to the ship and "printed on" the FPGA for immediate use. The advantages of using FPGA are that (1) the functionality of the FPGAs can be customized in the field, and (2) establish design could be obtained from the library of similar applications (such as microprocessors, digital signal processors, communication processors) to enable design re-use.

Lending credence to the use of FPGA is the assessment by Maier and Rechtin, who provided an assessment of the trend supporting the use of programmable semiconductor devices. They highlighted that "product developers used to build from relatively simple parts (such as groups of logic gates) are now using highly integrated microprocessors with most peripheral devices on the chip." This has brought about economies of scale in "semiconductor design and production which have pushed the industries toward integrated solutions where the product developer primarily differentiates through software, since the microprocessor-based products acquire their functionality by the software that executes on them" (Maier and Rechtin 2009, 148). Such trends have resulted in the microcontrollers becoming "so inexpensive and have such low power consumption that they can be placed in nearly every product, even throwaway products" (Maier and Rechtin 2009, 148). The latter point on throwaway products thus indicates

the feasibility of a “use and throw” approach proposed by the DPO CONOPS, which could further contribute to the reduction in life cycle cost through the reduction in planned and corrective maintenance requirements.

For the additively manufactured UAV, the use of FPGA brings about three key advantages. First is the use of common parts to implement a variety of different functions, thereby enabling a large number of similar parts to be carried onboard a warship but with possibly different implementations until they are programmed. Second, the use of such common parts allows economies of scale to be achieved, thereby reducing the overall cost for the implementation of an additively manufactured UAV and allowing a lower “barrier of entry.” Third, the use of common parts with just the software changes allows rapid configuration of the UAV and its associated uses to take place, thus allowing rapid evolution of the UAV design and its operational employment. This not only allows the latest development to be rapidly fielded, but also creates a situation where the potential adversary would no longer be able to reliably predict the capability of the navy deploying such additively manufactured UAVs for operational uses.

D. SUMMARY

In this chapter, the discussion focuses on the building blocks to actualize the DPO CONOPS of building the UAV onboard ship using additive manufacturing and delayed differentiation. In the section on additive manufacturing, it is shown that the additive manufacturing system could be used for the development of the UAV structures and control surfaces. While additive manufacturing systems are possible onboard ship, the constant motion of the ship may limit the use of certain types of additive manufacturing such as those using laser curing where the photopolymer or metal power may shift around the vat as the ship is experiencing pitch and roll. As such, it is suggested that fused deposition methods, such as those using the extrusion print head, may be used for shipboard additive manufacturing.

Having addressed the UAV structure and control surfaces, the next section assesses what might be the possible approach for the implementation of the electronics for the UAV where the use of COTS is proposed. This enables rapid assimilation of the latest in technological development, thus enabling game changing concept of operations to be rapidly conceptualized and configured.

In the discussion of COTS for the UAV’s electronics, it is also recognized that there may be a need for specialized electronics modules that control the UAV’s functionality. This is unlikely to be realized by COTS. As such, the use of FPGA was identified as a possible way ahead where dedicated control electronics could be obtained in-situ through the use of appropriate programs to implement the UAV’s control electronic.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. APPROACH TO DPO OF UNMANNED SYSTEMS TO ENHANCE SHIP'S MISSION FLEXIBILITY

Chapter IV explores the possible options to realize DPO of unmanned systems in-situ, as and when required. The approach to DPO builds upon the discussion of the building blocks to realize the unmanned systems as discussed in Chapter III: additive manufacturing techniques, use of COTS items and FPGA.

There will be five sections. The first section addresses the CONOPS to enhance ship's mission flexibility. The second section addresses the feasibility of the approach by assessing other similar developments. The third section addresses the operationalizing of DPO CONOPS for additive manufacturing of UAVs from the ship. The fourth section addresses the DPO of UAVs and the fifth section discusses the risks of mission fulfillment associated with the DPO of UAV.

A. CONOPS TO ENHANCE MISSION FLEXIBILITY FOR SHIP'S MISSION

The CONOPS to enhance mission flexibility for ship's mission is predicated on having the design readily available for download by the ship. Once downloaded, the UAV could be additively manufactured and deployed for the required mission. Upon successful completion of the mission, the UAV could be disposed of or be recycled for other uses. Enabling the additive manufacturing of a UAV would be the availability of a UAV design that has already been validated and made available for download by the ship through the DOD website, cloud storage or shipboard library of pre-downloaded UAV design. This could be in the form of the STL or the relevant file format for additive manufacturing. The crew from the ship selects the required UAV design by matching it to the intended mission, sends it for additive manufacturing, and then operates it.

With this CONOPS, only the manufacturing means may need to be embarked on the ship instead of a physical UAV system. This accounts for the implementation of the physical structure, control surfaces, and possibly the propulsion unit of the UAV. The physical structure could be the HTOL, VTOL or hybrid configuration discussed in Chapter II.

Similarly, the associated control software would be made available for the specific UAV design and could be retrieved or downloaded and incorporated to the UAV after it is programmed into the microchip. This would be the FPGA discussed in Chapter III where the special type command and control module for the UAV could be downloaded and implemented. The ship would also be equipped with COTS for the implementation of the autopilot, sensors, and navigation and power modules for the UAV.

For the GCS, the control software could similarly be downloaded and installed on the laptop that functions as the operator console. The interfacing to the radio frequency link could then be achieved through a modem or SATCOM. To realize the DPO CONOPS, the ship will only need to be equipped with the raw materials for additive manufacturing, the additive manufacturing system, the COTS items and the FPGAs.

In summary, the entire UAV design could be made available in softcopy and downloaded when the UAV is required. The specific software for the command modules for the command and control of the UAV, as well as the software for the GCS, could also be downloaded. With this approach, only generic COTS, FPGA and raw materials need to be carried by the ship. The differentiation will only occur when a specific UAV that best suits a mission requirement has been selected and printed for the mission.

B. FEASIBILITY OF APPROACH

This section analyzes the feasibility of rapid prototyping of UAVs. First, the thesis reviews other work in the rapid manufacturing of UAVs.

Aurora Flight Sciences of Manassas, Virginia, has constructed a thermoplastic drone system using the FDM technique with a commercial additive manufacturing system. The UAV is shown in Figure 25 (NAS 2014, 20). The initial prototype of the UAV was additively manufactured to assess the aerodynamic design, thus enabling the use of innovative structural arrangements and complex geometrical shape that is not possible to achieve using traditional manufacturing and construction technique. In this aspect, Aurora has in fact built and flown UAV with active sensors embedded into additively manufactured wings (NAS 2014, 20).

Figure 25. Examples of Small Aircraft with Additively Manufactured Parts by Aurora Flight Sciences. Source: NAS (2014, 20).

A similar exploration on the use of additive manufacturing systems has also taken off in the United Kingdom, where the faculty and students at Leeds University, England constructed a fully functional metallic prototype of the airframe and propulsion systems for a UAV. The exploration was done in collaboration with Airbus Group (NAS 2014, 20). In the United States, an additively manufactured UAV was developed by Virginia Tech using an Android phone to perform the control function as well as commercially available products to implement the GPS receivers and sensor modules.

There have also been trials on the use of additively manufactured UAVs additive manufacturing systems onboard ship. Advances were made when an additively manufactured drone was launched from a Royal Navy (R.N.) warship in July 15, shown in Figure 26. An additive manufacturing technique was used to develop the airframe and structure and COTS items were used for the guidance and control systems.

Figure 26. Additively Manufactured Drone Tested at Sea. Source: Marks (2015).

Figure 27 shows the use of an additive manufacturing system abroad the aircraft carrier USS *Harry S. Truman* (CVN 75) on November 27, 2015, in the Atlantic Ocean. The additive manufacturing system was a new addition to the fabrication labs. It enabled sailors to produce custom parts abroad ship using the additive manufacturing system. It was placed onboard USS *Harry S. Truman* and the amphibious assault ship USS *Kearsarge* (LHD 3) with the intent to enable the ships to be more self-sufficient as they deploy for missions. The initiatives have spurred ideas and brought about excitement on the endless possibilities aboard ships equipped with the additive manufacturing system (Vergakis 2015).

Figure 27. Uses of 3D Printer on Aircraft Carrier USS *Harry S. Truman* (CVN 75). Source: Vergakis (2015).

The preceding discussion on parallel development suggests that it is possible to develop and produce a UAV rapidly through the use of additive manufacturing technology. It also indicates the increasing use of additive manufacturing systems for the manufacturing of UAVs, as well as their use onboard ship. The trajectory of DPO CONOPS is in alignment with the proliferation of additive manufacturing systems and their uses onboard ship. It fuses the two ideas, with the additional consideration of delayed differentiation through the use of COTS to enable DPO for ships. To implement this CONOPS, the basic building blocks to realize the functional hierarchy of the UAV are shown in Table 19. Table 19 provides a summary of the possible components that build up the UAV. It also provides the cross references to the modules in the functional hierarchy that could be implemented.

Table 19. Possible Components for the Make-up of an Additively Manufactured UAV.

Types	Reference to the Functional Hierarchy	Components	Method of Implementation for DPO
Structure	7.0 Provide Structure 7.1 Provide Control Surfaces 5.1 Provide Payload Mechanical Interface 8.0 Provide Propulsion	UAV aero-structure, strength member, control surfaces, propellers, etc.	**Additively Manufactured**. Glass-reinforced polyester could be used to strengthen the additively manufactured structure. Construction could be a snap-on type with minimal assembly required.
Electronics	1.0 Provide Command and Control 1.1 Monitor UAV’s Health 1.2 Control UAV’s Movement	Guidance and Command module	**FPGA** *(The implementation could also include any microprocessor-based hardware that allows interfacing and programming.)*
	4.0 Communicate Internally and Externally 4.1 Receive Data and Command 4.2 Process and Interpret Data 4.3 Transmit Data 4.4 Process Data for Transmission	Communications module	**COTS items**—Hand-phone, tablet, radio systems
	3.0 Determine UAV and Target Information 3.1 Provide UAV’s Attitude (Orientation, Speed) and Altitude. 3.2 Provide Target Information (Bearing, Range)	Sensors	**COTS**—Sensors such as infrared and HDMI camera

Types	Reference to the Functional Hierarchy	Components	Method of Implementation for DPO
	3.3 Monitor Own Functionality		
	2.0 Provide Navigation 2.1 Determine UAV's Position 2.2 Determine Route (to commanded location)	Navigation systems	**COTS**—GPS and INS
Electrical	8.1 Provide Energy Distribution 5.0 Provide Payload Interface 5.2 Provide Payload Electrical Interface 5.3 Provide Payload Data Interface	Wiring, wiring harnesses, electrical connections.	**COTS**—Wires, wiring harnesses and electrical connections
Propulsion	8.0 Provide Propulsion	Propulsion	**COTS**—Motors or jet engine Or **Additively Manufactured**—Electric motor or jet engine.
Power	6.0 Provide Power 6.1 Provide Stored Energy 6.2 Provide Alternate Energy Source	Batteries	**COTS**
		Solar panel	**COTS**

From the discussion of the UAV's context and functional hierarchy in Chapter II, it can be seen that there can be many possible permutations on how the UAV can be developed, and hence the flexibility in the approach to DPO of a UAV using additive manufacturing and the use of COTS. Table 19 identified the techniques that are most feasible in realizing the UAV. It can also be seen that the same COTS can be used for different types of UAV airframe, thereby allowing delayed differentiation.

C. OPERATIONALIZING DPO CONOPS FOR ADDITIVE MANUFACTURING OF UAVS FROM SHIP

The thesis will now extrapolate the application of such technologies for use in the naval environment.

1. Assumptions

The key assumptions for the rapid development of the UAV in-situ include:

- The design of the UAV is already available

- The additive manufacturing approach has been developed
- The software for the GCS and UAV has been developed and available for downloading into the UAV's electronics
- The COTS is already available onboard the ship
- The prototype UAV has been integrated and verified

2. Additive Manufacturing of UAV

Using additive manufacturing, the parts of a UAV could now be printed and configured. The possibilities are juxtaposed against the functional hierarchy of the unmanned systems to show what could be considered and configured (see Table 19).

3. UAV Parts to be Additively Printed

The possible components that can be additively manufactured include:

- body, control surfaces of the UAV
- motor and gears
- engines

Based on the current additive manufacturing technology, it is assessed that the structure, control surfaces and motor can be printed. This means that the UAV would be complete if the COTS items comprising battery or power sources, guidance electronics, communication modules and payload, and special-to-type electronics (i.e., the command module) are available.

D. DPO OF UAV

1. Structure and Control Surfaces

In operationalizing the concept, the structure can be printed in separate parts and designed for easy installation, as opposed to the printing of the entire structure. This would allow subsequent repair by replacement, as well as utilizing an array of additive manufacturing systems to speed up the production process. The print volume of the current additive manufacturing machine varies between different additive manufacturing systems; with the largest being 914 x

610 x 914mm using the Fortus 900mc FDM printer discussed in Chapter III. Therefore, it is expected that the design of the UAV allows the additive manufacturing of the structure parts that would then be integrated after the parts are printed utilizing a “snap-on” approach to enable ease of installation and assembly. A key design feature would be the structural integrity and strength of the connection to prevent premature failure in flight.

2. UAV Components

The capability of additive manufacturing is not limited to structural or static components. The motors that drive the propeller could also be additively manufactured. The structure could be additively manufactured and the electrical wiring that generates the rotating magnetic field for the rotor could be manually wound.

Jet engines can also be additively manufactured. In 2015, GE successfully fired up a fully additive manufactured jet engine measuring 1-foot long by 8-inches tall (30 by 20cm) to 33,000 rpm. It was made entirely of additively manufactured parts using direct laser metal melting (DLMM), printing which is similar to the SLS process. The design is created for remote control model planes, however, as opposed to conventional commercial engines. Figure 28 shows the jet engine that was developed using the DLMM process (Szondy 2015).

Figure 28. The Additively Manufactured Parts of the Jet Engine.
Source: Szondy (2015).

The ability to additively manufacture the jet engine enables high performance UAVs to be developed. The use of DLMM hinges on the use of lasers for fusion of the metal powder on the vat, however, which in turn may be affected by the operation on a non-stable platform. As such, unless the design tolerances have been considered in the design, or the platform is stable

(e.g., a LPD type as opposed to the LCS platform), there are limitations for the use of DLMM onboard ship. Nonetheless, the DLMM could be used at naval base facilities for implementation of the jet engine for the UAV.

3. UAV's Electronics, Sensors and Control Module

The UAV's electronics, sensors and control module could be implemented using COTS items or FPGA. The possible COTS items for UAV are discussed in Chapter III.

The FPGA can be programmed to be the UAV's command module, which needs to be customized for the specific type of UAV (e.g., HTOL, VTOL or hybrid), as well as the payload required (e.g., control of the aerial camera and/or SAR on the UAV). The FPGA could also be pre-programmed, tested and validated and made available for storage and/or transmission for subsequent download from the computer. Once the code is downloaded, it could be programmed through an interface device to the FPGA.

E. SUMMARY

The DPO CONOPS to additively manufacture UAVs will add to the ship's mission flexibility and, hence, ability for the ship's mission to be expanded. The additive manufacturing of UAVs by academia and industry, and its exploration by the military, signifies the potential for future work using additive manufacturing techniques. The CONOPS to realize DPO of UAVs onboard ship is more than just additive manufacturing as it combines the use of COTS to enable delayed differentiation and FPGA to provide the specific control functions that are unique to each UAV design. Combining the three building blocks is thus the central thrust of the DPO CONOPS proposed in this thesis. Although the assessment of the current development in academia, industry and the military indicates that the approach is still in the preliminary stage, it is a feasible approach to take to enhance ship's mission flexibility. Nonetheless, there is risk to mission fulfillment associated with the DPO approach if components and/or modules of lesser reliability (compared to MIL-SPEC) are used. This represents a trade-off and the implementation should address the mission specific needs. As such, if the UAV mission is expected to last approximately 1,000 hrs, the least reliable components should be rated for at least 1,000 hrs of operation to prevent mission failure due to equipment failure. Thus, the reliability of the UAV would then be limited by the least reliable component(s).

THIS PAGE INTENTIONALLY LEFT BLANK

V. EXPANDING CONCEPT OF OPERATIONS WITH DPO-ENABLED SHIPS

The DPO CONOPS allows for rapid introduction of new capabilities in-situ, which provides the potential for tactical surprise. This chapter discusses the possible concept of operations (CONOPS) enabled by the DPO of unmanned systems in-situ. The adoption of DPO could also be extended to the CONOPS in the surface and underwater warfare domain with the implementation of unmanned surface systems and the unmanned underwater systems. This chapter discusses the CONOPS on the use of additively manufactured UAVs to enhance ship survivability.

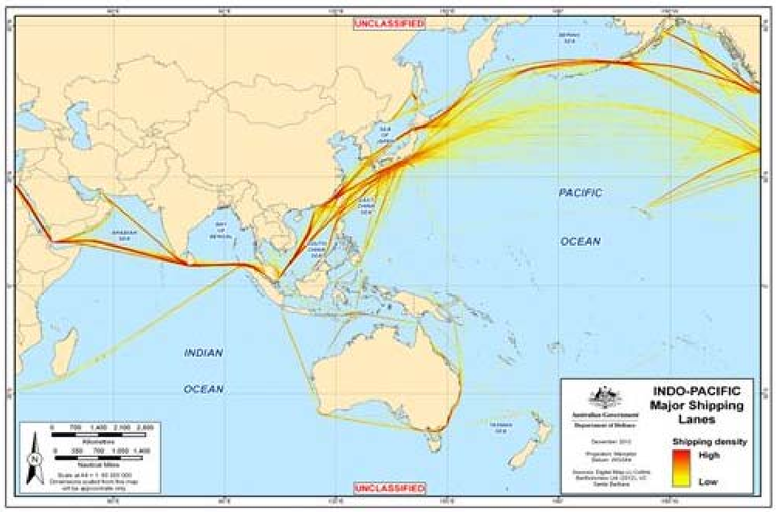
A. CONCEPT OF OPERATIONS—USE OF ADDITIVELY MANUFACTURED UAVS TO ENHANCE SHIP SURVIVABILITY

The ship will need to operate in the littorals, which can be near island groups and is dense in maritime traffic. This is the region where activities from the land could influence a ship's survivability.

1. Potential LCS Area of Operation

The Singapore Strait is a critical sea line of communication (SLOC) to many countries including the U.S., China, Japan and Singapore. An estimated one third of the world's GDP and three quarters of the world's oil and natural gas transits the strait annually. The security of the Singapore Strait is thus a critical issue for countries whose flow of seaborne trade and resources are at stake. Terrorists, such as Islamic State, can attempt to dent confidence in the SLOC security of the Singapore Strait to indirectly threaten the interests of the targeted countries. One way to do so is to exploit small boat attacks on security elements that use the strait; such as the LCS that could be deployed to the region. The small boat can be disguised to look like a local fishing boat. It can appear to be carrying out fishing activities or hide behind large vessels in the narrow strait, only to spring a close-by surprise attack on the LCS to increase the chances of a successful attack. The small boat attacker can employ weapons that are accessible and have significant lethality. These include rocket-propelled grenades (RPG), anti-tank weapons (ATW) and improvised explosive devices (IED). This study thus assesses and provides recommendations on the survivability of the LCS in such a threat scenario.

Many countries, including big powers such as the U.S., China and Japan and also Singapore (being a maritime nation), depend on the Singapore Strait for resource transportation and international trade. Figure 29 shows various countries' shipping routes passing through the Singapore Strait. SLOC security in the Singapore Strait is therefore a key concern to these countries.



Source: Defence White Paper 2013. Department of Defence, Australian Government

Figure 29. Singapore Strait—A Vital Shipping Passage for Many Countries. Source: Australian Government Department of Defence (2013, 13).

Zooming in, the Singapore Strait is a cluttered environment with heavy shipping, see Figure 30. The strait is an extreme stretch of coastal water that is much more congested than blue or brown waters. It is estimated that at least 1000 vessels move around daily in the strait.

Figure 30. Snapshots of the Busy Singapore Strait. Source: Kemp (2014).

A defining characteristic is the narrowness of the strait. The narrowest width is 3.2 to 3.4 nautical miles (nm) between the closest islands on both sides of the strait (see Figure 31). The two-way shipping lane is even narrower at around 1 nm width or 0.5 nm per shipping lane. Ships travelling within the lane can travel as close as 0.2 to 0.3 nm to one another. This means that small boats can choose to hide behind large vessels to spring attacks at close range on the target, resulting in a short reaction time for defensive actions to be taken by the LCS.

South of the strait, the close proximity of land to the shipping lane, with its ports, villages, jetties and coastal foliage, presents suitable opportunities to prepare for attacks on security elements and high-value shipping in the Singapore Strait.

Compounding the challenge of vessels in close proximity is the traditional small boat fishing area in the center of the strait (see Figure 31). Small boat attackers can exploit these areas to stage attacks on the target by first disguising as innocuous fishing boats. When the target approaches at very close range, the small boat attackers could suddenly launch their weapons or quickly close in to detonate explosives.

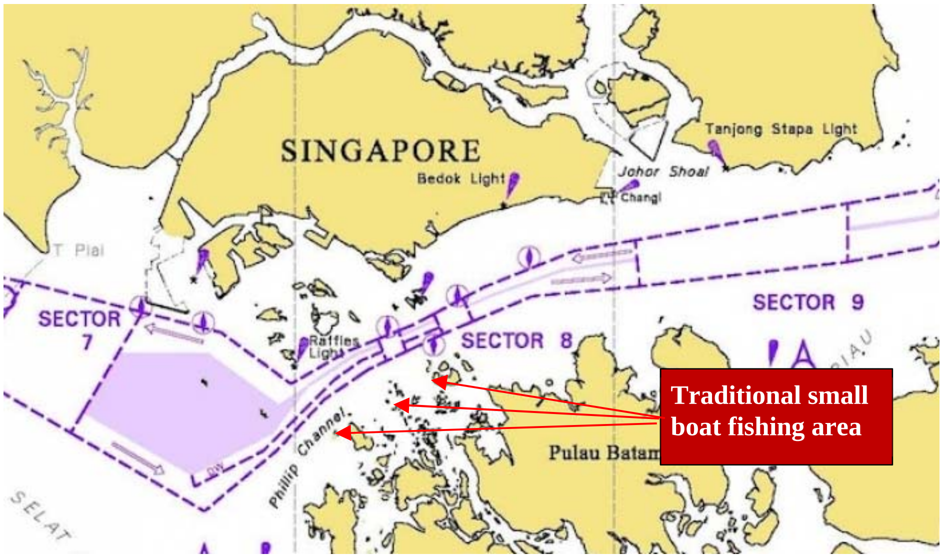


Figure 31. Possible Disguised Small Boat Threats in Traditional Fishing Areas. Adapted from Hand (2013).

In summary, the Singapore Strait is important as a key SLOC to many countries for resources and trade. Possible small boat threats can use islands to the south of the strait to prepare for attacks. The narrowness of the strait, coupled with traditional fishing activities, provides a golden opportunity for a possible small boat threat to pre-position as close as possible, either hiding behind large vessels or masquerading as a fishing vessel, to spring a very short-range small boat attack.

Following the insights gained from the operating environment, the analysis shifts to the threat—its source, motivation and attack modes. The influence of Islamic State's call to create an Islamic caliphate has become popular for jihadists in the Southeast Asia region. It has become more likely that Islamic State supporters may have gone to Syria and Iraq to fight for ISIS, only to return with a hardened ideology and sophisticated terror expertise. The potential terrorists could be trans-national and cross borders to prepare and launch attacks on land and at sea, thus making it difficult for any country alone to deal with the threat.

Knowing that the major powers are concerned about the impact of SLOC security on their economic and resource lifelines, potential terrorists can attempt to dent confidence in SLOC security as well as in trade and energy shipping, by targeting the security elements that patrol the SLOC. The possible type of boat used in the attacks is shown in Figure 32. This boat is called a "sampan" in the region, similar to how "skiffs" is a local term used in the Middle East/African

region. It is typically used for fishing in the Singapore Strait. The sampan is small, fast and difficult to detect by radar. It typically has one outboard motor and can reach speeds in excess of 30 knots. As can be seen in the picture, it is not inconceivable for the sampan to possibly hold one or more RPGs along with IEDs. From a distance, it is not easy to identify whether the sampan is a threat or an innocent fishing boat, even when using binoculars, EO/IR or radar. One would have to go close or board the sampan to confirm the presence of weapons. It is still relatively easy to spot the sampan and observe its fishing activity in daylight as there is a visible contrast with the sea water. This would deter attackers from attacking in daylight and spur them to exploit the cover of darkness for small boat attacks.

Figure 32. Sampan as Possible Small Boat Platform to Launch RPG and IED Attacks. Source: Sailing Totem (2014).

Using the innocuous cover of a fishing boat carrying out fishing activities, the attacker could choose to attack at the last moment when the LCS passes close-by, or hide behind large vessels to mask their presence and then attack as the LCS reaches the closest point of approach. The attacks could be made by a single boat or multiple boats for greater destruction. Multiple boats could choose to attack the LCS from different directions to stretch the LCS's defenses and increase the probability of closing to weapons range.

The sampan would use rudimentary equipment to execute its observe, orientate, decide, act (OODA) loop. Being a small boat, it would not have radar or EO/IR capabilities. The attacker

would rely on the naked eye, binoculars and/or portable night vision devices (NVD) to detect and track the LCS. The sampan would use the outboard motor for propulsion and maneuvering to close on the LCS and bring it into weapons range. When in range, the attacker relies on his eyes and hands to aim and fire the weapon at the LCS (or detonate the weapon in the case of an IED).

On the choice of attacking weapons, the weapons of RPGs, anti-tank weapons (ATW) and IEDs are discussed, as these are more lethal than small arms and likely to be accessible through the black market and terrorist networks. In a higher-end scenario, the small boat attacker could use both RPG/ATW attacks followed by suicidal IED blast to inflict maximum damage to the LCS. RPGs are relatively easy for terrorists to obtain from the arms black market and are typical weapons used to threaten ships. The RPG-7 is one of the most commonly available RPGs made by the Russians. It has a propelled flight of 500m but is usually effective at around 200m (Engelbrecht 2011).

Anti-tank weapons (ATW) could also be used to target the LCS. There are several types of anti-tank weapons. These include recoilless rifles, which are similar to RPGs, and anti-tank missiles (Adams 2015).

IEDs could also be used to inflict significant damage on the LCS. They are relatively simple to make with a little research, time and training. They can also be easily hidden, for example, inside fishing containers.

As covered in this analysis, ISIS as a source of the small boat threat remains real. The threat is likely to exploit the fishing boat or “sampan” disguise to enable a surprise attack at close range to the LCS. The small boat attackers are likely to use RPGs, ATWs and/or IEDs as these weapons are more accessible and are lethal. A high-end threat scenario is the combined use of RPG/ATW and IED to cause significant damage to the LCS.

2. Survivability Analysis

The LCS’s survivability analysis was conducted. Survivability is a function of susceptibility and vulnerability. According to Ball (2003, 4), the definition of survivability is given by the following:

$$Survivability = 1 - Sus * Vul$$

where Sus is susceptibility and

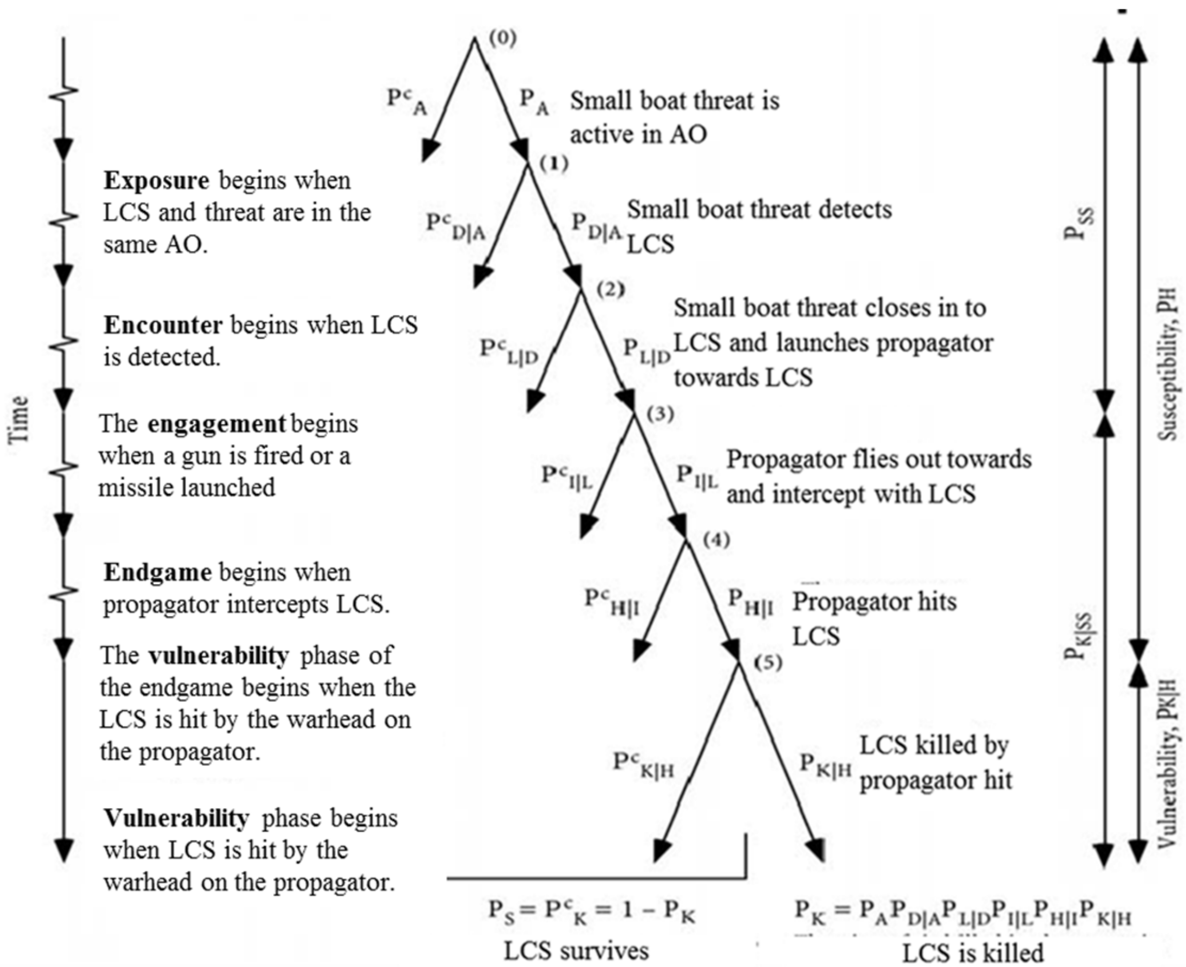
Vul is vulnerability

There are 12 aspects to the survivability enhancement concepts (Ball 2003, 537–584 and 696–725). Of those, six relate to susceptibility reduction as shown in Table 20.

Table 20. Survivability Enhancement Concepts.

Survivability Enhancement Concepts	
Susceptibility Reduction	**Vulnerability Reduction**
1. Threat warning 2. Signature reduction 3. Expendables 4. Threat suppression 5. Tactics 6. Noise jamming and deceiving	7. Component redundancy 8. Component location 9. Passive damage suppression 10. Active damage suppression 11. Component shielding 12. Component elimination/replacement

To assess the survivability of the LCS operating in the littoral, an example of which is the Singapore Strait, reference was made to the kill chain for a small boat threat to the LCS, as shown in Figure 33.



Key:

P_A = Probability that the threat is **A**ctive

$P_{D|A}$ = Probability of **D**etection given an **A**ctive threat

$P_{L|D}$ = Probability that warhead is **L**aunched (fired) given **D**etection of the LCS

$P_{I|L}$ = Probability that warhead **I**ntercepts LCS given a warhead **L**aunch

$P_{H|I}$ = Probability that a damage mechanism from the warhead **H**its the LCS given a warhead **I**ntercept

$P_{K|H}$ = Probability that the LCS is **K**illed given a **H**it by a damage mechanism from the warhead

Figure 33. Kill Chain for Small Boat Threat against LCS. Adapted from Ball (2003, 11).

One approach to addressing the survivability of the LCS is to address the susceptibility. This is because armoring of modern naval vessels is not usually done due to the weight that it adds to the ship and the concomitant reduction in maximum speed, endurance, and a host of other performance trade-offs. For instance, a larger amount of “fuel and a larger propulsion

system would be required to move the ship at the desired speed" (Adams 2015). The space traded-off could have been used to equip the warship with more weapons or sensors. Therefore, not armoring the modern naval vessel is reasonable as the consideration is that naval battles will be conducted beyond visual range and be highly dependent on the range of the surveillance radar as well as the maximum weapons engagement range. In the event that an anti-ship missile from an aircraft or other naval vessel is launched toward the naval vessel, the armoring is unlikely to offer additional protection. The threats from small boats, however, reverse the situation. "There is a need to provide armor protection on the ship to defeat small arms, blast and fragmentation attacks. This is to give adequate protection to the crews and critical components housed within the ship so as to reduce cascading damage that will kill critical components, including the crew" (Adams 2015). These have important implications. In examining the kill chain, it can be seen that the probability of kill for the LCS can be given by:

$$P_K = P_A P_{D|A} P_{L|D} P_{I|L} P_{H|I} P_{K|H}$$

To reduce the P_K, the possibilities could be done to reduce $P_{D|A}$, $P_{L|D}$, $P_{I|L}$, $P_{H|I}$ without addressing $P_{K|H}$, which might include armoring. One possible mitigating approach is to stop the threat in its tracks before the threat materializes. This is covered in the next section.

3. Addressing Susceptibility of LCS

The narrow Singapore Strait and the close proximity of shipping to one another (about 300–700m) coupled with the high traffic density in the area of operations will mean the need for the LCS to monitor multiple targets that may be suspicious, while the small boat threats can hop from vessel to vessel and hug close behind a large merchant vessel before launching a close-by surprise attack on the LCS. See Figure 34.

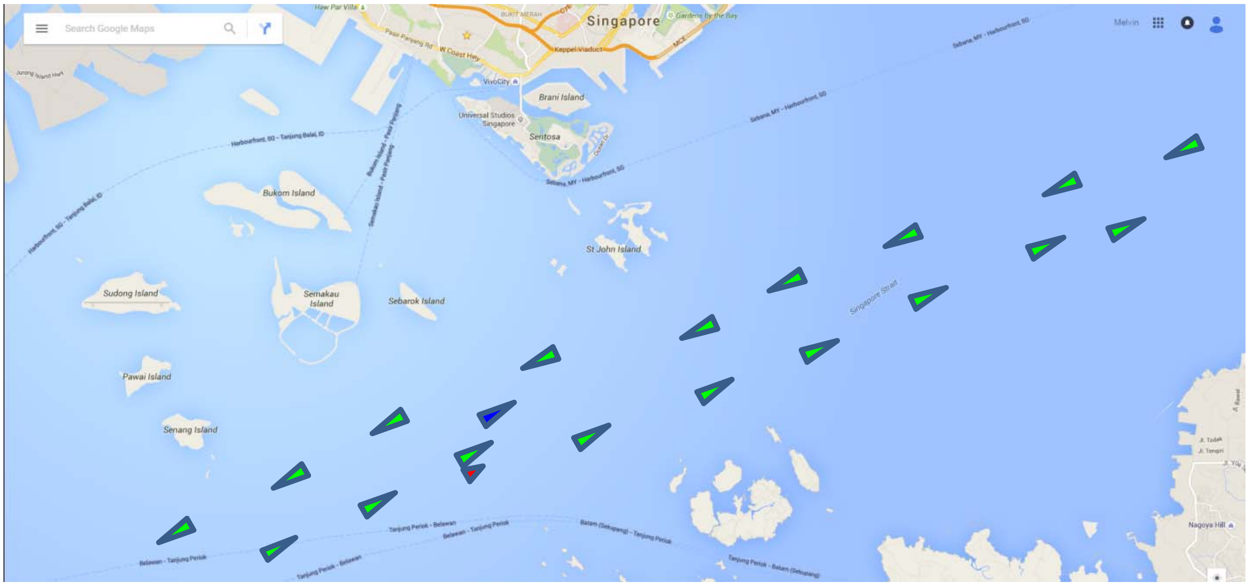


Figure 34. Example of Small Boat Attacker (Red) Staging for Close-by Surprise Attack on LCS (Blue). Adapted from Google Maps (n.d.).

Thus, the challenge is not so much to extend detection and tracking ranges but to be able to survey the far side of large merchant vessels that serve as possible staging positions for close-by surprise attacks on the LCS, as well as survey the potential small boat attacker assimilating amongst the genuine fishing sampans before the LCS approaches.

The onboard sensors of the UAV cover the surveillance gaps without putting the LCS in harm's way. This will allow good situational awareness to be provided to the LCS in a timely manner to affect timely response to any small boat threats. As constant surveillance is a monotonous task, the RPV could have built-in intelligence for target processing and threat detection. The data from the RPV will then be used by the ship's command team for threat prioritization and weapons assignment.

With the relative speed advantage of 10–15 knots for the attacking sampan translating to about 13 secs to close every 100m, the LCS would have very little reaction time from the moment a threat is detected until it attacks the LCS. The physical size of the boat would also mean difficulty in putting rounds into the small boat, and there may be insufficient time to execute the right rules of engagement (RoE). The limitation to use proportional force would further mean that unless the small boat is sufficiently warned, the patrol vessel could not just

take out the targets with the main gun. All this reduces the overall reaction time from the patrol vessel to eliminate the threats.

4. CONOPS for Additively Manufactured UAV-Forward Surveillance Using Constellation of UAVs

The LCS may not have the UAV or USV embarked when deployed. As such, the DPO concept would enable the ship to "print" the UAV when required. A possible CONOPS is shown in Figure 46. When transiting in high threat zones, the UAV is printed in-situ to provide constant surveillance of the LCS. The data required from the UAV would be the visual image of possible threats to the LCS. This could be carried out in the form of a security "bubble" that provides an aerial view of the sea 5 to 10 nm away from the LCS. The images obtained by the UAVs would be sent back to the ship where they could either be assessed by the UAV operators or the image recognition software incorporating pattern recognition (e.g., support vector machine, artificial neural networks) to sieve out possible threats using heuristics or rules-based approaches.

Figure 35 shows a possible arrangement of UAVs forming a constellation around the LCS. UAVs shown in blue are the surveillance UAVs, whereas UAVs shown in yellow could carry a small amount of explosives and are intended for detonation on impact or command detonated when ordered. The yellow UAVs are to prevent any potential threats from further threatening or damaging the LCS. The intention for the yellow UAVs is to disable the armaments or the propulsion of the small boat threat(s). Figure 36 shows the UAVs deployed to investigate suspicious small boat threats.

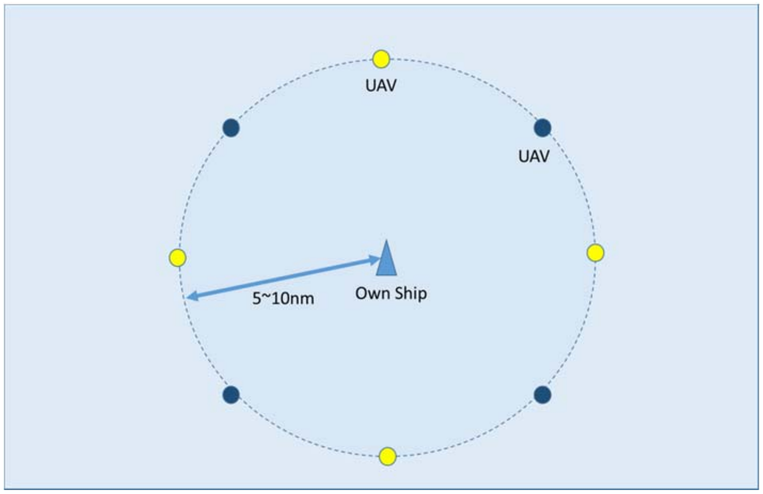


Figure 35. Possible CONOPS for Enhancing Ship Survivability in the Littorals—Constant Surveillance Zone Using a Constellation of UAVs.

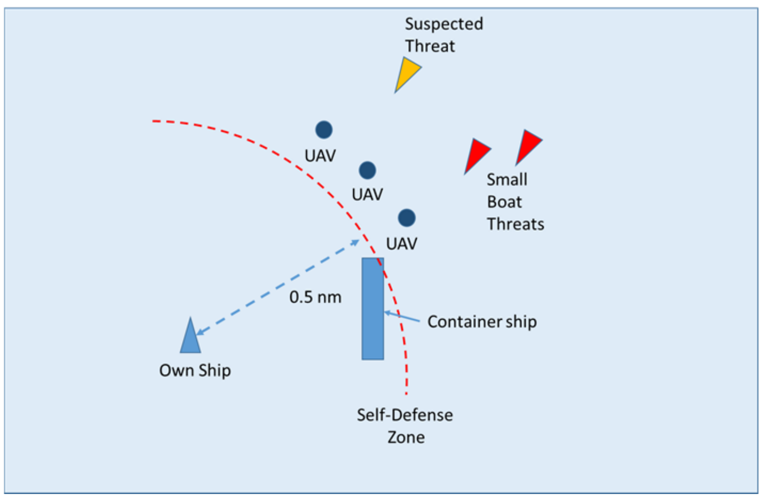


Figure 36. Possible CONOPS for Enhancing Ship Survivability in the Littorals—Threat Investigation.

From Figure 36, the LCS could deploy multiple UAVs (three as shown in the figure) for the identification of the small boats and classify them as threats before they enter the self-defense zone. This would help overcome the challenge of seeing over the "far-side," the ship behind which the small boat threats are hiding and awaiting the opportunity to spring a surprise attack on the unsuspecting LCS. These overcome the limitations of the LCS radar, which would not be able to:

- discern the small boat as laden with explosives without the visual identification

- detect the small boat in time, given that the container ship would have prevented the radar signals from reaching the small boat and returning to the LCS's radar to identify the presence of the small boat

By deploying the UAV and obtaining the visual images, the LCS would have adequate reaction time to prevent a suicide attack. If explosives are carried on the UAV, the UAV could be used to "ram" into the engine of the small boat to disable its propulsion, hence neutralizing the threat. Correspondingly, if there are weapons mounted and it is observed to be ready for firing at the LCS, the UAV could ram into the weapon to neutralize the threat.

B. SUMMARY

The DPO of UAV when ships are deployed will herald a whole new range of possibilities hitherto unheard of. These are especially for ships such as the LCS that are forward deployed, operating singly and to whom the supply chain may be challenged to complete the last mile delivery of items. Adoption of DPO is expected to further enhance the ship's capabilities, providing both tactical and operational flexibility.

The use of additive manufacturing for unmanned systems offers much mission flexibility to the surface combatants. The widespread use will nonetheless require implementation time, proficiency in use of additive manufacturing onboard ship, and a culture of acceptance. Going ahead, it is assessed that a gradual approach to implementation would be necessary to continuously "do-try-do" where the design is implemented, trialed, refined and implemented. As such, it is assessed that the possible immediate use of AM could be the implementation of tactical UAVs where the performance is not as demanding as MALE and HALE with respect to operating altitude, range and endurance. The use of such tactical UAVs could be useful for the situation where there is a need to rapidly increase the number of UAVs to conduct operations or in support of operations. An example is the conduct of SAL operations for survivors after a tsunami or a suspected plane crash in the sea. The ship being deployed to the area for conduct of the search could additively manufacture the UAV in-situ and deploy it to extend its surveillance range without having the need to return to base to be equipped with the UAV. This provides the opportunity to rapidly deploy the UAV without the need to maintain a logistics tail to support and sustain the UAV. Additionally, additive manufacturing could also be used to provide battle damage repair of UAVs to ensure continuity of operations and support.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. ANALYSIS OF FEASIBILITY FOR IN-SITU MANUFACTURING OF UAVS

Chapter V discusses one possible CONOPS for the use of UAVs to enhance ship survivability. This chapter addresses the operational and technical feasibility of rapidly manufacturing UAVs using the techniques proposed. It will attempt to answer the following questions: How long would it take? What capabilities are needed onboard the ship? And what COTS would the ship need?

A. OPERATIONAL AND TECHNICAL FEASIBILITY OF RAPIDLY MANUFACTURING UAV ONBOARD SHIP

There is a need to assess both the operational and technical feasibility of rapidly manufacturing the UAV onboard ship as espoused by the DPO CONOPS.

1. Operational Feasibility

The operational feasibility of rapidly manufacturing UAVs onboard ship is predicated on the ease of performing the DPO CONOPS by the operator and the time required to perform the additive manufacturing. This is because the ease or difficulty of performing the DPO CONOPS would then affect the ship's readiness, whereas the time required to perform the additive manufacturing would mean that the ship would have a reduction in crew to man their duty stations when the UAV is to be additively manufactured.

In assessing the operational feasibility, it is assessed that the DPO CONOPS would require the service member to follow simple instructions (which could be downloaded from the DOD website along with the UAV design). The task includes loading the raw materials to the 3D printer, uploading the design to the 3D printer and printing it, the post processing of the printed materials, the joining of the printed materials into the UAV structure, as well as the installation of the COTS to the UAV structure. The last task involves the connection of electrical cables, as well as the fastening of securing screws or devices to the UAV structure. It is assessed that the task could be easily undertaken, although it requires dedicated time to perform.

On the time to perform the "printing" of the UAV in-situ, it is assessed that the CONOPS will be feasible if the time required to "print" the UAV is less than 24 hours. This is in

cognizance of the fact that the ship will need time to transit from home base to the assigned area of operation.

2. Technical Feasibility

The technical feasibility to realize the DPO CONOPS is concern with the weight, energy and space required onboard. From Table 16, the heaviest additive manufacturing system weighs 500 kg. It is assessed that the weight is equivalent to some of the major modules onboard ship (e.g., the transmitter and receiver rack for the radar) and as such does not pose an issue to the ship's stability or weight distribution. It is assessed that the major space requirements would be the space for the storage of the raw materials, COTS, the additive manufacturing system, a work area for the integration of the UAV, and separate storage for hazardous materials such as batteries and/or explosive. With the LCS as a platform under study, it is assessed that there is sufficient space for the storage of raw materials and COTS items. The additive manufacturing system could be installed in the hangar or a separate container previously identified for the LCS's mission module. Given that the size of a possible additive manufacturing system is under 1m x 1m x 1m (see Figure 21), it is assessed that there is sufficient space on the LCS for the installation of the additive manufacturing system as well as the incorporation of the work area for the integration of the UAV structures and the COTS items. Although it is assessed that the weight and space required for the installation of the additive manufacturing system to realize the DPO CONOPS is feasible, there is also a need to access space for the repair and/or replacement of the additive manufacturing system if it requires corrective maintenance.

On the energy consumption requirement, it is assessed it could be fulfilled by the ship's power supply. The highest amount of energy is 346 kWh per kilogram (see Table 15) of 3D material printed using the fused deposition approach; thermoplastic polymers are the raw material used. Nonetheless, the circuit breakers and electrical distribution network will need to be sized up to be able to cater to the most demanding process using fused deposition modeling (NAS 2014, 46).

B. TIME REQUIRED TO ADDITIVELY MANUFACTURE THE UAV

The success of the proposed DPO CONOPS to rapidly manufacture a UAV in-situ depends on the time required to "print" the UAV. As such, a model was developed to assess the

time required to “print” the UAV. The model assumes that the build time of an additively manufactured UAV will involve four key steps as shown in Figure 37.

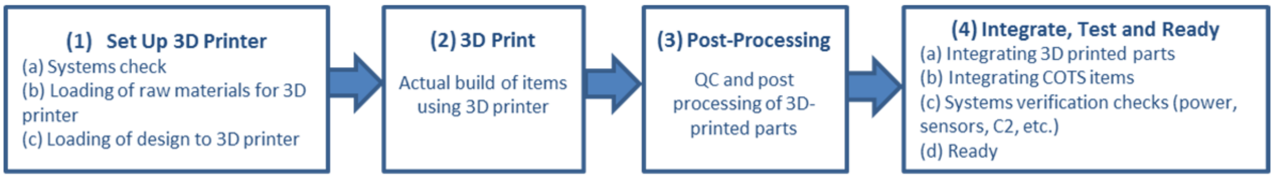


Figure 37. Four Key Steps for the “Printing of UAV.”

The first step includes setting up the additive manufacturing system or the 3D printer. This includes the conduct of systems check to ensure that (a) the print head or the extrusion head is not clogged with the raw materials (thus affecting the print quality), (b) the print-bed is clear of debris that may affect the deposition of the raw material onto the print-bed during the additive manufacturing process, and (c) the 3D printer is working as expected. It also includes the loading of raw material for the 3D printer to ensure that the job could be completed without interruption (i.e., sufficient material). The final portion for the first step is the loading of the design to the 3D printer to be printed. This includes the assessment of the STL file, ensuring the orientation of the print is correct (i.e., minimizing the amount of scaffolding required, thus economizing on the raw materials and the post-processing tasks of removing the scaffolding).

The second step is the actual build of the items using the 3D printer. The total duration of the 3D printing is dependent on the size, orientation (affects the scaffolding requirement), speed of the printer, temperature required to melt and fuse the raw materials, speed of the 3D printer, and quality of the print head (e.g., if it is easily clogged).

The third step is the post-processing. This is where the quality of the print job is inspected for defects. Additionally, the scaffolding that was built in step 1 will be removed in this stage.

The fourth and final step is the integration and testing of the UAV before it is ready for actual use. The integration is necessary as the UAV could comprise multiple parts that are separately printed by the same or different 3D printer. The step also involves the bringing together of the COTS components that comprise the various modules such as the sensors and navigation modules to build up the UAV. Once the UAV is integrated, a system check will be

undertaken to verify the functionality of the key modules. Such functionality checks include the communications module that receive commands from the ground control station to the UAV, the interpretation of the command and the correct control of the actuators that drive the control surfaces.

Given the diversity of UAVs that could be built for different missions (i.e., the variations in size, endurance and/or performance), the four steps thus represent an amalgamation of activities that are necessarily broad. As such, the model provides assessment based on Triangular Distribution so that the user can enter the minimum, most likely and maximum for each step. The input portion of the analytical model is shown in Figure 38.

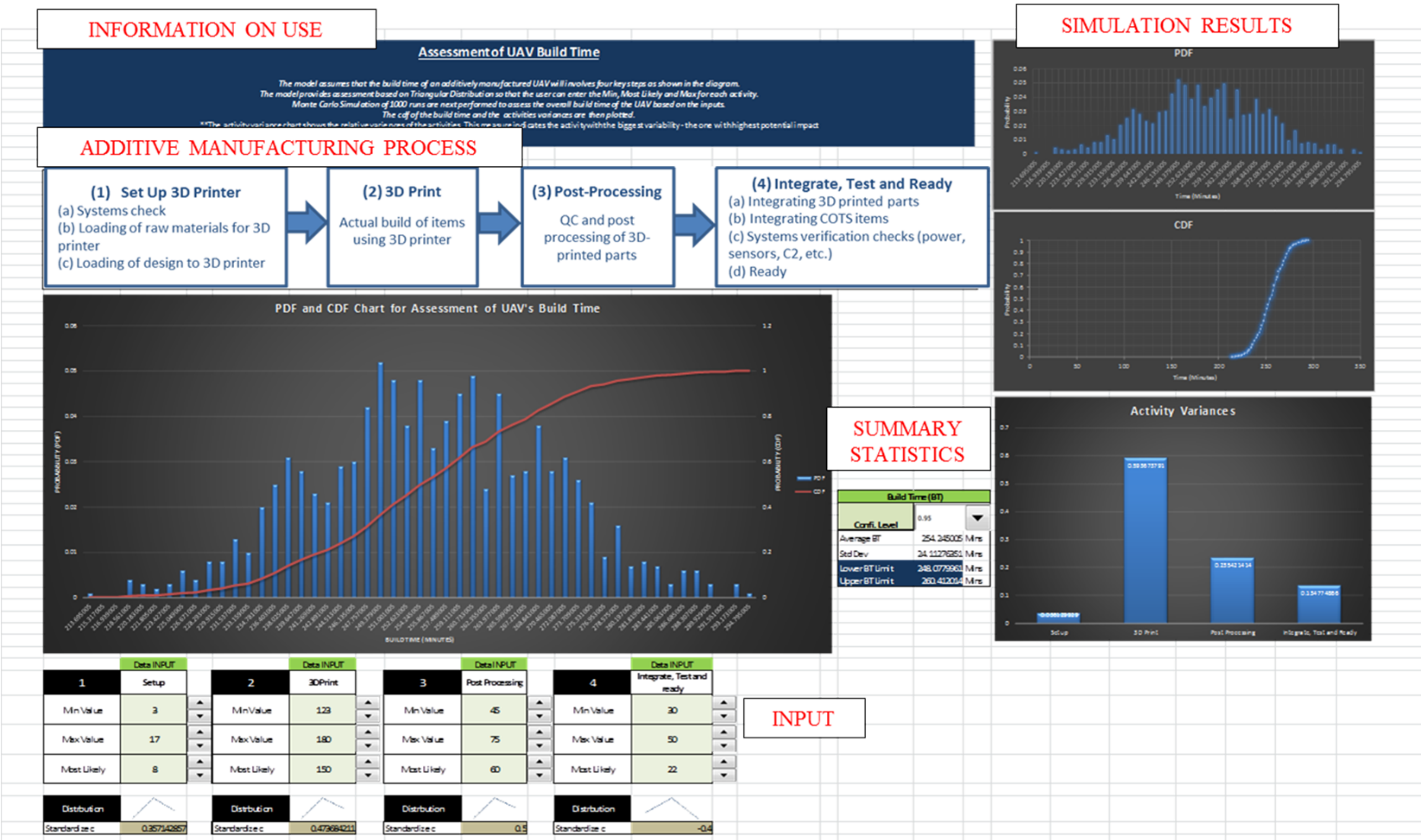


Figure 38. Screenshot of the Input to the Analytical Model.

The inputs to the build process are as tabulated in Table 21 for each of the four steps. It is assumed that the UAV to be built is the tactical UAV type, which is small in size and useful for operations up to 5 km in operating radius. This type of UAV would be useful for realizing the CONOPS to enhance the LCS's survivability in the littoral. As such, it is assessed that the 3D printing process will take between 95 to 105 minutes, with a post-processing time ranging from 10 to 30 minutes, and the final integration and test requiring from 20 to 30 minutes. The assumption used in the assessment is that each 3D print process allows multiple parts to be printed at one go, and multiple 3D printers could be used to reduce the overall printing time to the most complex items. The only limitations would be space, energy and cost of the 3D printers.

Table 21. Notional Input to the UAV Build Process.

	Data INPUT		Data INPUT		Data INPUT		Data INPUT
1	**Setup**	2	**3D Print**	3	**Post Processing**	4	**Integrate, Test and ready**
Min Value	10	Min Value	95	Min Value	10	Min Value	20
Most Likely	13	Most Likely	100	Most Likely	15	Most Likely	22
Max Value	15	Max Value	105	Max Value	30	Max Value	30

With the input to the UAV build process defined, Monte Carlo simulation of 1,000 runs is performed to assess the overall build time of the UAV. The cumulative density function (CDF) of the build time and the activities variances are then plotted. The output is shown in Figure 39.

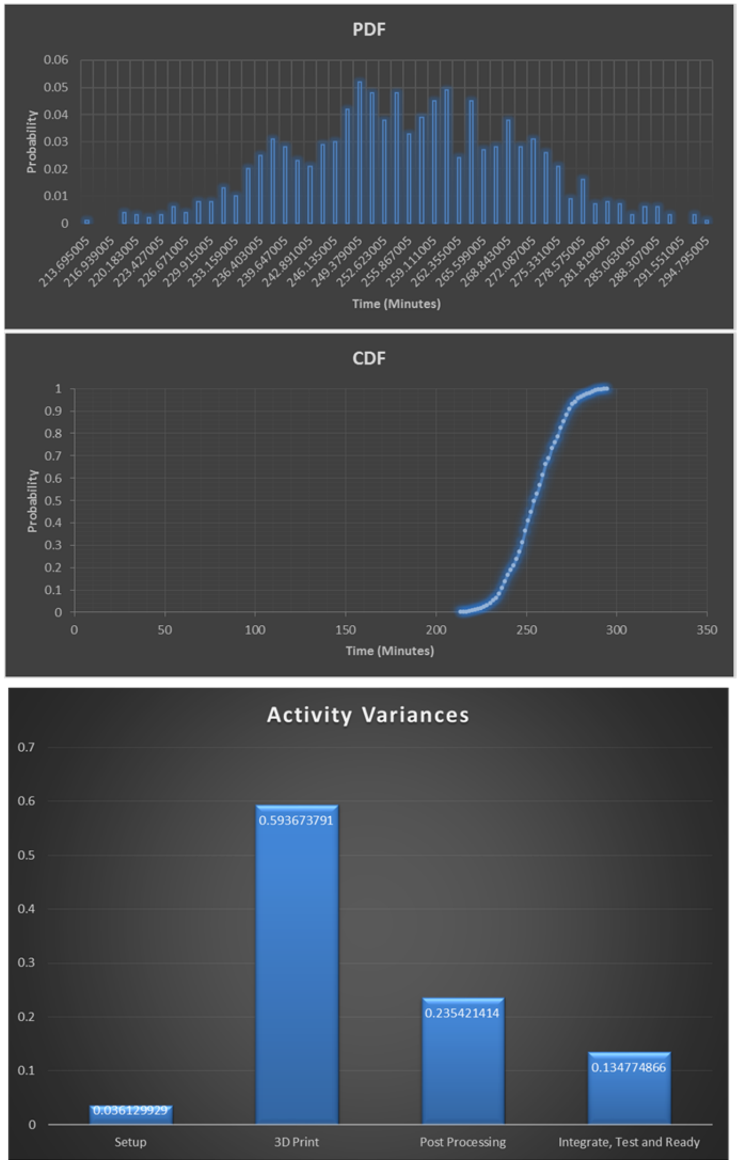


Figure 39. Output of the Analytical Model for the Assessment of the UAV Build Time.

The output comprises a frequency distribution of the expected build time for the UAV. From Figure 39, it can be assessed that there is a 90% confidence level (based on the input data) that the UAV build time is approximately 275 minutes or under five hours. This is an important aspect in assessing if the UAV could be manufactured in a timely enough manner for the required mission. Since five hours is typically less than the usual transit time from home-base to the area of operations, it is determined that the time to build the UAV to support the CONOPS proposed for enhancing LCS survivability is feasible.

In order to assess possible improvement to expedite the printing of the UAV, additional information and features are included in the analytical model. Supplementing the information is the breakdown of the major contributors to the build time through the bar chart. Through the assessment of the major contributors (through the bar chart showing the activity variances), assessment could be made on reducing the variances so as to reduce the overall build time of the UAV.

Figure 40 shows that the 3D print process (step 2) contributes the largest variance. This is expected as the process is likely to be the most involved and is highly dependent on the material properties of the raw material, the complexity of the build/design, the quality of the printer, the size of the object to be printed, the geometry and a host of other considerations, such as the reliability of the 3D printer. To have better control over the build time, a separate "production line" or "server" could be incorporated to perform parallel processing. Such consideration is also applicable to steps 1, 2, 3 and 4. Nonetheless, there are limits to the number of such parallel processing. This could be due to either resource constraint such as insufficient manpower and/or space onboard the ship to perform the setup (step 1); post processing (step 3); integration, test and ready (step 4), or economic considerations on the equipping of additional additive manufacturing systems (3D printers).

Having identified the step with the greatest variance, the next logical step would be to address how that can be improved. In doing so, it is also important to assess the point of diminishing return. The decisions could then be on the number of service members assigned to assemble the UAV, or the number of additive manufacturing systems to speed up the production process.

A further step could be taken to have ~50–75% of the UAV's components be common across different UAV designs. This allows common components to be additively manufactured prior to any mission tasking, and ensures that the parts that are specific to the UAV design (i.e., the remaining ~25–50%) are additively manufactured in-situ and on demand for the intended mission. This could be further explored if the DPO CONOPS is accepted.

C. CAPABILITIES NEEDED ONBOARD THE SHIP

The use of additive manufacturing techniques to realize the DPO may require a completely new set of knowledge, skills and abilities (KSA) across the organization to actualize the espoused concepts. The service member may require new and/or additional training curricula to equip them with the repertoire of skills to fulfill the different levels of requirements for the required roles. To do that, there is a need to identify the KSA requirement vis-à-vis the existing additive manufacturing technologies juxtaposed against the DPO CONOPS. For example, system engineers will need to be trained to be able to design, modify, assess, model and build the database for the DPO CONOPS. Test and evaluation (T&E) engineers will need to be able to assess the DPO models that have been designed by the system engineers before they can be used. At the shipboard level, the service member on the ship will be able to choose the most appropriate model, download, print and operate it when it is required.

To enable the above, there is a need to ensure that the design and installation instructions are robust. It is envisaged that one of the design aims is to require minimal operator interventions and minimal integration work required by the operator. A "snap-on" approach akin to the LEGO TECHNIC concept is envisioned, where instructions for the installation are clearly laid out graphically. This would reduce the cognitive demand expected of the shipboard operator and hence allow multiple UAVs to be printed and assembled continuously without overwhelming the shipboard operator. It is assessed that such an envisioned state is possible to be realized where the operator will need to perform simple install/dismantle tasks while following simple instructions.

Although the capability requirements are assessed to be feasible with the simple install and dismantle tasks that could be performed by any service member, the way ahead includes identifying and scoping the possible pilot implementation trial so that the DPO CONOPS can be progressively reviewed and enhanced prior to wider implementation. Along with this is the concurrent identification and development of training requirements to actualize the DPO CONOPS._This is an important aspect as it enables wider proliferation if an untrained service member could easily be tasked to operate the additive manufacturing systems, obtain the desired results from the additive manufacturing system, and assemble the UAV without being trained in

the first place. While it is envisioned that the service member onboard ship could carry out the simple install and dismantle operations to assemble the UAV, it is also contingent on the design of the UAV and the instructions to facilitate the ease of realizing the in-situ manufacturing of UAVs with minimal or no prior training for the service member.

D. COTS REQUIRED TO REALIZE RAPID MANUFACTURING OF UAV ONBOARD SHIP

To realize the rapid manufacturing of UAV onboard ship, three key constituents were identified: additive manufacturing of the structural items and/or control surfaces, COTS for the implementation of the specialized electronics and/or functions, and FPGA for the implementation of the command module.

The UAV mission specific to the CONOPS to enhance LCS survivability would require COTS for navigation, autopilot, radar, data processing, and communications. The possible COTS items were identified in Chapter III and summarized in Table 17. The COTS items identified and captured in Table 17 are assessed to be small in size, requiring minimal power, and enable ease of integration to the UAV. The COTS are readily available from multiple different suppliers supplying COTS of similar or comparable technical specifications. This is an important advantage as it allows multiple sourcing without fear of obsolescence, and free market competition where there will be continuous improvement and where more capabilities could become available at a lower price.

E. OTHER CONSIDERATIONS: UAV RELIABILITY

Although the concept for the in-situ manufacturing of the UAV involves the “use-and-throw” approach, the reality is that the ship, and in particular the LCS when deployed, may only carry a finite amount of raw materials and COTS. As such, if the UAV is required for prolonged use such as the case for the prolonged operations in the littoral by the LCS, then it is desirous that the UAV does not fail before the completion of the mission. As such, an analytical model is built to assess the reliability of the UAV. The additively manufactured UAV could be made up of multiple components and/or modules. In creating the model, the following assumptions were made.

Assumption 1. COTS items are used as the building blocks for the additively manufactured UAV. This enables the Navy to harness the advantage of employing the latest advances in technologies; it is expected that the inventory of COTS would not be more than three years old, although this is an arbitrary estimation.

Assumption 2. COTS are expected to be progressively used up and replenished with newer items. These items could be the same, more reliable, more technologically advanced, or more reliable and more technologically advanced.

Assumption 3. The failure data or the mean time between failures (MTBF) may not be readily available. Therefore, the failure distributions of the modules are modeled using a triangular distribution. The use of triangular distribution allows the user to enter the **minimum**, **most likely** and **maximum** MTBF that is expected to represent the modules under study.

Assumption 4. Failure of any modules constitutes a system failure. Thus, the minimum of the MTBF (per simulation run of each of the 1,000 runs) for all the eight modules is taken. This assumes that all the modules are critical for the operations of the UAV. If a certain module is assessed not to be critical, a large value (e.g., 1,000,000) for the module could be assigned to the module when the parameters are input to the model. This is because the model is focused on the "weakest link" or the minimum MTBF of all the modules per simulation run in building up the failure distribution.

Assumption 5. The construction of the model further assumes that the UAV will comprise eight modules as highlighted in the discussion of the functional hierarchy.

The user interface is shown in Figure 40. Once the user enters the data, Monte Carlo simulation of 1,000 runs is performed to compute the overall reliability of the UAV based on the inputs. The reliability of the UAV can be obtained through the CDF plot. Summary statistics showing the average MTBF of the UAV as well as the standard deviation and confidence levels for 80%, 80%, 95% and 99% can also be obtained. For the notional data used, the average MTBF is 5168 hrs with a standard deviation of 429 hrs. The 80% confidence level for the UAV MTBF is between 2900 hrs and 7436 hrs. Thus, if the UAV is expected to last for less than 2900 hrs, there would be no issue with the reliability of the UAV. If the UAV is expected to work between 2900 and 7436 hrs, there is 80% chance that it will be defective. If this is not

acceptable, then more reliable components could be used for the UAV. Such approach is likely to be iterative. The bar chart is used to provide information on where the highest leverage (the modules with the highest payoff in improvement to the UAV's reliability) might be in the attempt to improve the UAV's reliability. To enable sensitivity analysis to be conducted easily, improvement factors are included beside each module in the model.

The use of the improvement factor is to enable assessment of changes in MTBF through reliability enhancement and/or use of MIL-SPEC as opposed to COTS items. A one-to-ten improvement factor can be chosen. Slider bars are included beside each module to enable sensitivity analysis by adjusting the improvement factor while assessing the relative performance changes over the cumulative density function and the bar chart.

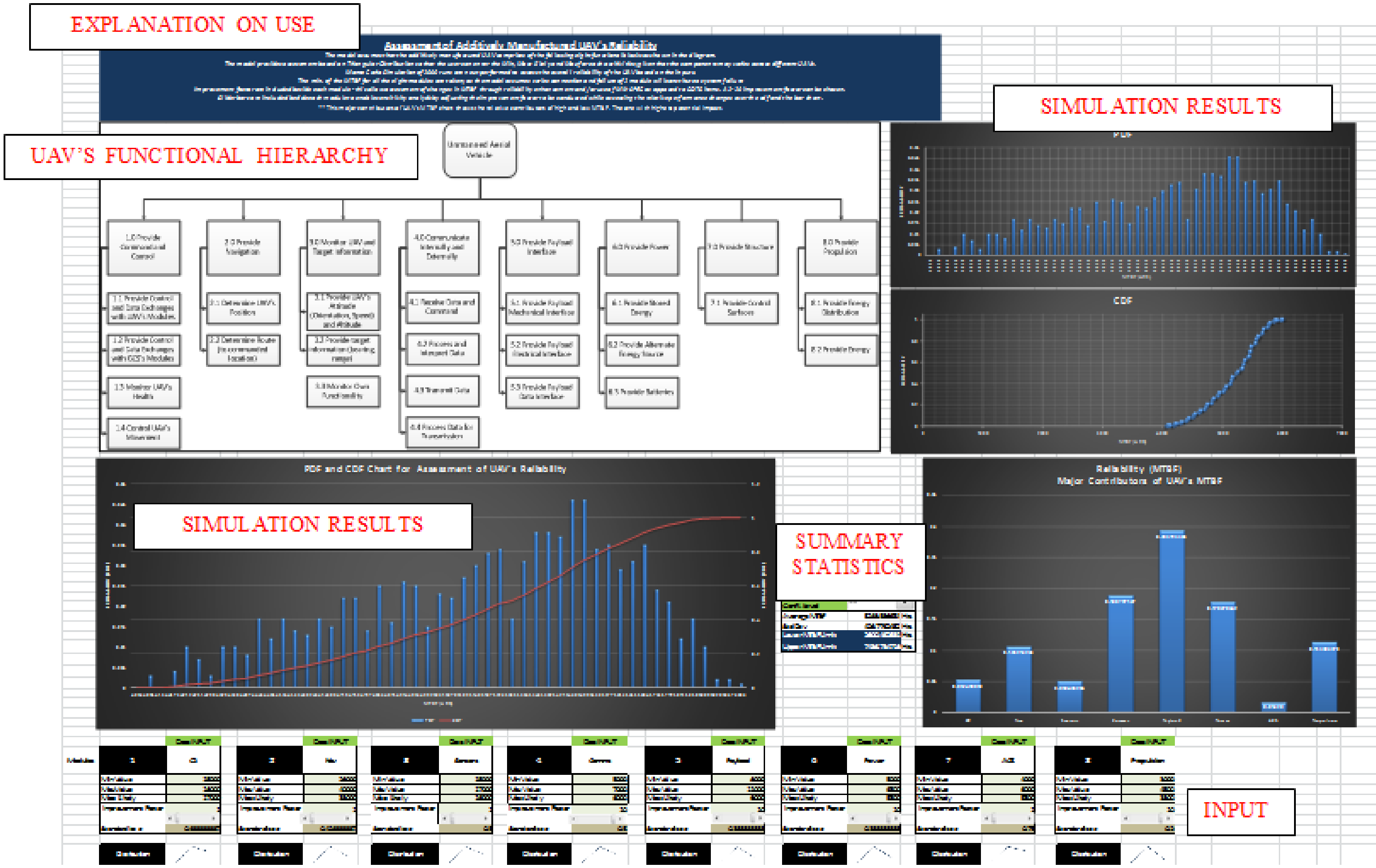


Figure 40. Screen Shot of the User Interface for Assessing Reliability of the Additively Manufactured UAV.

Through the use of improvement factors (ranging from one to 10) for each of the modules, a sensitivity study could be conducted on the use of a relatively more expensive module to enhance the reliability of the UAV. The changes and its impact can be seen in the relative contribution of the improvement from the bar chart that is plotted (reliability (MTBF)—Major Contributors of UAV's MTBF). In the creation of the improvement factor, it is assumed that the improvement factor of one is used for existing COTS items, whereas the improvement factor of 10 could be the substitution of COTS items with military specification items.

Figure 41 shows a sample whereby the propulsion would be the limiting factor for the reliability of the UAV, whereas Figure 42 shows the result after the improvement factor was applied to the identified limiting factor (i.e., the propulsion system). From the notional data, it can be seen that the next limiting factor is the sensors, followed by the C2 module. Done iteratively, it allows the user to configure the most cost effective and reliable (in a relative sense) UAV for the intended mission.

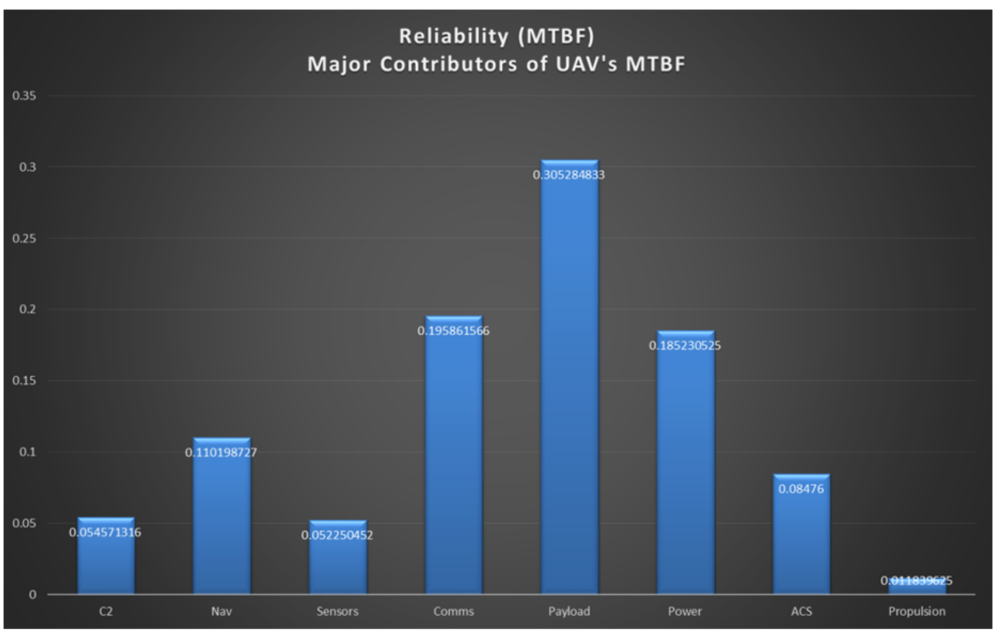


Figure 41. Comparison of Limiting Factors on the Reliability of the UAV.

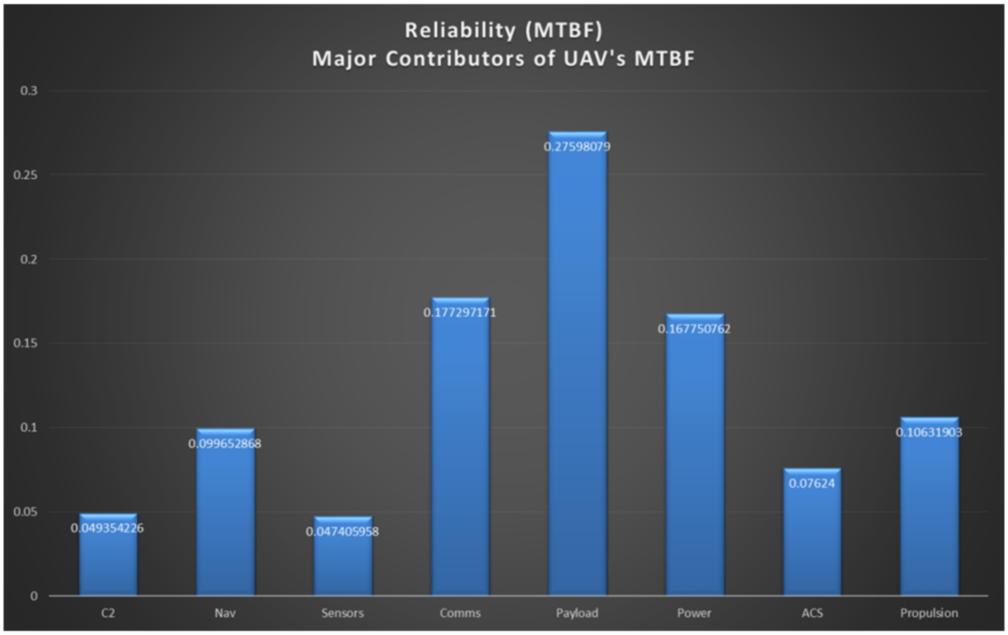


Figure 42. Reliability of the UAV (with Improvement Factor Applied).

The reliability assessment model thus allows the configuring of a UAV to the cost through selection and COTS modules that are much more affordable than MIL-SPEC modules.

F. SUMMARY

The chapter brings together the concepts to realize the DPO CONOPS for in-situ manufacturing of UAVs and assesses the feasibility of using it for the CONOPS to enhance LCS survivability in the littoral. Clearly, the CONOPS could be realized from both the technical and operational perspective, with a possible “printing” time of approximately five hours for one UAV, assuming that multiple 3D printers could be installed onboard ship to expedite the additive manufacturing processes and the number of 3D printers to be embarked are limited by only space, energy consumption and cost. A further step could be taken to reduce the overall additive manufacturing time by ensuring that ~50–75% of the UAV’s components are common across different UAV designs and are additively manufactured prior to any mission tasking. As such, only parts that are specific to the UAV need to be additively manufactured in-situ and on demand. Additionally, the reliability of the UAV could be tailored to the specific mission duration required by careful choice of the types of COTS (with its associated MTBF) to be used. Furthermore, the service member is capable of supporting the DPO CONOPS by printing the

UAV onboard ship when it is required and assembling it after it is printed. As such, the capability to print a UAV to enhance LCS survivability when operating in the littoral is a near-term possibility once the design is available and the ship is equipped with the additive manufacturing systems, raw materials, COTS and FPGA.

VII. CONCLUSION AND FUTURE WORK

The use of additively manufactured UAVs is in the nascent stage of development. While there are ready components for the implementation of the UAV, the reliability aspects of the components will limit the continual use without failure. This will have an impact on the reliability and hence the ability to fulfill the intended mission. This is in contrast to the use of components with military specifications for a typical military UAV, where reliability is crucial to ensure mission fulfillment.

The advancement of the additive manufacturing approach offers a host of benefits to the Navy. By leveraging the rapid advancement of additive manufacturing techniques and careful choices over the types of materials and the additive manufacturing machines, and combining it with the use of COTS and/or FPGA components, it is possible to equip a ship that is forward deployed with capabilities that were only available on the drawing board or the nascent stage of development when the ship first left port.

The use of tactical UAVs and its CONOPS are explored in this thesis. This is because the uses of a tactical UAV are operationally relevant and operationally significant. Given that it is unmanned, there will also be minimal safety impact if it fails. On the same note, failure of a tactical UAV may only have minimal impact on the strategic outcome of the mission. Proven successful and accepted, it is envisaged that the possibilities would be game changing for future equipping and naval operations. Given the right COTS components, blueprint, and adequacy of raw materials, it is entirely possible for the UAVs to be additively manufactured. The additive manufacturing system could even be used to print another additive manufacturing system to increase the overall throughput for printing a mission system such as a UAV, UGV, USV and/or any parts or components that may be required in-situ, without being “shackled” and thus limited by the logistics tail and the associated timelines. It is thus possible that the proposed DPO of unmanned systems using additive manufacturing with delayed differentiation would provide the armed forces and the combatant commander with mission flexibility.

A. FUTURE WORKS

To reap the full potential of the espoused DPO CONOPS, new ground remains to be explored. The future works are as identified through the discussion in the thesis and are summarized as follows:

1. Stable Manufacturing Platform

The additive manufacturing techniques require a stable platform to work on. A ship, however, is inherently unstable due to its environmental factors such as sea condition. Thus, "any externally induced vibrational forces can negatively impact the integrity of the final part" that is additively manufactured (NAS 2014, 46). This includes "vibrational loads induced by the activities of the crew members, the background" vibrational "white noise" from the operating machinery such as generators and ship engines, or the occasional change of heading adjustment; these "can all affect the integrity of a part manufactured with additive technologies" (NAS 2014, 46). During the course of "additive manufacturing, material (mass) is constantly being deposited" (NAS 2014, 46). This process creates a "dynamically changing geometry for the end product" (NAS 2014, 46). As the end product grows in cross section, disturbance torques may change. If not compensated, they will affect the end result, whose "effects will be pronounced in the additive manufacturing of object with large cross-sectional areas." As such, future work could study a vibrational isolation system for the additive manufacturing system to enable shipboard operations, even in rough seas. This would provide a stable platform for ensuring high-quality manufacturing. The vibration isolation system is envisioned to be a stable platform that has "some level of dynamic control system" to compensate for the vibrational motion. To do that, it could include a stabilization system, damping systems, "gyroscopes, and sensors capable of indicating rate and direction of motion" (NAS 2014, 46). Besides the exploration of vibration isolation techniques, other areas of research could involve the design of the additive manufacturing system using electrostatic charge and/or vacuum techniques to "glue" a defined layer of raw materials (such as metal powder) to the previous additively manufactured layer before it is fused by the laser.

2. Types of Joints for the UAV to Enable Rapid Integration After Additive Manufacturing

In the discussion on the use of additive manufacturing, it is postulated that the UAV will not be additively manufactured in its entirety. Instead, it is expected that the UAV is to be broken down into its constituent parts where they are individually printed, post processed and integrated. Merits of such an approach include: (a) the ability to "split" the jobs up across different additive manufacturing systems and (b) localizing the print failure, where failure of one part will have minimal impact over the entire build time and material wastages as opposed to the printing of an entire UAV. Thus, by breaking the UAV down to its constituent parts, the UAV is expected to be additively manufactured in a shorter time and with better predictability over its build time. Nonetheless, there is a need to ensure that when the constituent parts of the UAV are integrated, the strength of the joints is robust and not easily compromised during the execution of the mission. Joints such as the screw and bolt or a snap-on approach, as well as their relative merits, should be explored. The objectives are to reduce the integration time and time to print additional parts for the integration using the additive manufacturing systems, robustness of the joints, and final integrity of the UAV. It is envisaged that several categories of 'joining techniques' could be developed, such as the joining of structural components and integration of the COTS to the structural components

3. Types of Materials and the Associated Material Properties to Provide the Levels of Performance for the Additively Manufactured UAV

The types of materials, the associated material properties, and their strength and durability are important factors to consider so that the UAV can carry out its intended mission in the actual operating environment. Given the diversity of materials available for additive manufacturing, there is a need to limit production to the types of materials that possess superior material properties for the range of UAV missions that are expected to be undertaken. The research on the choice of material(s) should ideally converge on a material selection that can fulfill a wide range of UAV missions so that the ships need not embark many different types of materials to additively manufacture the UAV.

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF REFERENCES

3DSystems. 2014. "3D Printer Buyer's Guide—For Professional and Production Applications." Accessed March 8, 2016. http://www.3dsystems.com/files/2014_white_paper_3d_printer_buyers_guide_web.pdf.

———2015. "European Space Agency Investigates Additive Manufacturing DMP Parts for In-Space Satellite Engines." Accessed March 8, 2016. http://www.3dsystems.com/learning-center/case-studies/european-space-agency-investigates-additive-manufacturing-dmp-parts.

——— 2016a. "3D Systems Launches ProX DMP 320 for High Precision, High Throughput Direct Metal Printing." January 4, 2016. Accessed March 7, 2016. http://www.3dsystems.com/press-releases/3d-systems-launches-prox-dmp-320-high-precision-high-throughput-direct-metal-printing.

——— 2016b. "3D Systems Advances Multijet Printing Capabilities with Projet MJP 3600 and Enhancements for ProJet MJP 5500X." January 4, 2016. Accessed March 8, 2016. http://www.3dsystems.com/press-releases/3d-systems-advances-multijet-printing-capabilities-projet-mjp-3600-and-enhancements.

3D Printers Canada. 2011a. "The Fortus 900mc Production 3D Printer." Accessed March 10, 2016. http://www.3dprinterscanada.com/fdm-production-series-fortus-900mc.php#Tabs:Materials.

——— 2011b."Objet 3D Printer Comparison Chart." Accessed March 11, 2016. http://www.3dprinterscanada.com/3d-printer-comparison.php.

Abaco Systems. 2016. "mCOM10-K1 Datasheet." Accessed March 21, 2016. https://www.abaco.com/download/mcom10-k1-datasheet.

Advanced Navigation. 2015."Spatial Fog Dual." Accessed March 21, 2016. https://www.advancednavigation.com.au/product/spatial-fog-dual.

Australian Government Department of Defence. 2013. "Defence White Paper 2013." Accessed March 21, 2016. http://www.defence.gov.au/whitepaper/2013/docs/WP_2013_web.pdf.

Austin, Reg. 2010. *Unmanned Aircraft Systems: UAVS Design, Development and Deployment*. AIAA education series. Chippenham, Wiltshire, UK: American Institute of Aeronautics and Astronautics.

Barnhart, R. K., S. B. Hottman, D. M. Marshall, and E. Shappee. 2012. *Introduction to Unmanned Aircraft Systems*. Boca Raton, FL: CRC Press.

Ball, Robert E. 2003. *The Fundamentals of Aircraft Combat Survivability Analysis and Design*. 2nd Ed. American Institute of Aeronautics and Astronautics Education Series. Reston, VA: American.

Blanchard, B.S., and W.J. Fabrycky. 2011. *System Engineering and Analysis.* Prentice-Hall International Series in Industrial and Systems Engineering. Englewood Cliffs, NJ: Prentice Hall.

BrainyQuote. 2016. "Albert Einstein Quotes." Accessed Apr 21, 2016. http://www.brainyquote.com/quotes/quotes/a/alberteins385842.html.

Christopher, Adams. 2015. "ME4751 Aircraft Combat Survivability" (lecture, Naval Postgraduate School, Monterey, CA, Spring 2015).

Chua, C.K., K.F. Leong, and C.S. Lim. 2003. *Rapid Prototyping, Principles and Application*. 2nd ed. Singapore: World Scientific.

Chua, S. L. 2014. "Piloting a Drone." Accessed February 2, 2016. https://www.mindef.gov.sg/imindef/resourcelibrary/cyberpioneer/topics/articles/features/2014/apr14_fh.html#.V6zRXvkrK70.

Concept Laser. 2015. "Machine Solutions." Accessed March 21, 2016. http://www.conceptlaserinc.com/machines/#M2_Anchor.

Department of Defense. 2003. "Unmanned Aerial Vehicle Reliability Study." Washington, DC: Office of the Secretary of Defense.

———. 2010. *Defense Acquisition Guidebook. Chapter 5—Life-Cycle Logistics*. Accessed January 21, 2016. https://acc.dau.mil/CommunityBrowser.aspx?id=489744.

———. 2013. *U.S. Army Unmanned Aircraft Systems Roadmap 2010–2035*. Fort Rucker, Alabama: Office of the Secretary of Defense.

Fahlstrom, Paul Gerin, and Thomas James Gleason. 2012. *Introduction to UAV Systems*. 4th edition. Chichester, West Sussex: John Wiley.

Freebody, Marie. 2015. "Design-Driven Manufacture: 3D Printing Is Reshaping Industry." *Photonics*. Accessed January 21, 2016. http://www.photonics.com/Article.aspx?AID=57776.

Geiger, D.R. 2000. *Winning the Cost War—Applying Battlefield Management Doctrine to the Management of Government*. New York: Writer's Showcase.

Gibson, I. 2002. *Software Solutions for Rapid Prototyping*. London: Professional Engineering Publishing.

Gibson, I., D., W. Rosen, and B. Stucker. 2010. *Additive Manufacturing Technologies—Rapid Prototyping to Direct Digital Manufacturing*. New York: Springer.

Gledhill, T. J., Eric Mercer, and Michael A. Goodrich. 2013. "Modeling UASs for Role Fusion and Human Machine Interface Optimization." *IEEE International Conference on Systems, Man, and Cybernetics*: 1929–1937. Accessed November 19, 2015. http://dx.doi.org/10.1109/SMC.2013.332.

Google Maps (n.d.). Accessed Jul 21, 2016. https://www.google.com/maps/@1.1794336,103.8397464,11.75z.

Gupta, S. G., M. M. Ghonge, and P. M. Jawandhiya. 2013 "Review of Unmanned Aircraft System (UAS)." *International Journal of Advanced Research in Computer Engineering and Technology* 2(4), April.

Harbaugh, Jennifer. 2015. "Space Station 3-D Printer Builds Ratchet Wrench to Complete First Phase of Operations." NASA. Accessed February 8, 2016. http://www.nasa.gov/mission_pages/station/research/news/3Dratchet_wrench/.

Hamblen, James O., Tyson S. Hall, and Michael D. Furman. 2006. *Rapid Prototyping of Digital Systems—Quartus II Edition*. New York: Springer.

Hand, M. 2013. "Nine Missing after Barge Capsizes off Singapore." *SeaTrade Maritime News*. Accessed February 27, 2016. http://www.seatrade-maritime.com/news/asia/nine-missing-after-barge-capsizes-off-singapore.html.

IMSAR. 2015. "NSP-3." Accessed March 12, 2016. http://www.imsar.com/pages/products.php?name=nsp_3.

——— 2015. "Viper LS." Accessed March 12, 2016. http://www.imsar.com/pages/products.php?name=viper.

Intellectual Property Office. 2013. "3D Printing—A Patent Overview." United Kingdom: IPO.

Joint Air Power Competence Centre. (2014). "Remotely Piloted Aircraft Systems in Contested Environments—A Vulnerability Analysis." Accessed January 11, 2016. http://www.auvsishow.org/auvsi2015/Custom/Handout/Speaker9477_Session1008_3.pdf.

Kemp, T. 2014. "Crime on the High Seas: The World's Most Pirate Waters." *CNBC*. Accessed February 14, 2016. http://www.cnbc.com/2014/09/15/worlds-most-pirated-waters.html.

Kristol, William. 2004. "The Defense Secretary We Have." *Washington Post*. December 15. Accessed January 31, 2016. http://www.washingtonpost.com/wp-dyn/articles/A132-2004Dec14.html.

Leon, Engelbrecht. 2011. "FactFile: Bazalt RPG-7 Rocket Propelled Grenade and Launcher." Accessed January 15, 2016. http://www.defenceweb.co.za/index.php?option=com_content&view=article&id=12907:fact-file-rpg-7&catid=79:fact-files&Itemid=159.

Leigh, S. J., Bradley R.J., C. P. Purssell, D. R. Billson, and D. A. Hutchins. 2012. "A Simple, Low-Cost Conductive Composite Material for 3D Printing of Electronic Sensors." *PLoS ONE* 7(11): e49365, 2012, doi:10.1371/journal.pone.0049365.

Marks, Paul. 2015. "British Navy Warship Tests a 3-D-Printed Drone at Sea." *MIT Technology Review*. Accessed January 31, 2016. https://www.technologyreview.com/s/539586/british-navy-warship-tests-a-3-d-printed-drone-at-sea/.

Maier, Mark W., and Eberhardt Rechtin. 2009. *The Art of Systems Architecting*. 3rd ed. Boca Raton: CRC Press.

Measurement Specialties. 2012. "MS5611-01BA03 Barometric Pressure Sensor, with Stainless Steel Cap." Accessed February 27, 2016. http://www.meas-spec.com/downloads/MS5611-01BA03.pdf.

PhaseOne Industrial. 2013. Accessed February 27, 2016. http://industrial.phaseone.com/downloads-brochures.aspx.

Piqué, Alberto, and Douglas B. Chrisey. 2002. *Direct-Write Technologies for Rapid Prototyping Applications: Sensors, Electronics and Integrated Power Sources*. San Diego: Academic Press.

Ragsdale, Cliff T. 2012. *Spreadsheet Modeling & Decision Analysis—A Practical Introduction to Management Science*. Edition 6e. Mason, Ohio: South-Western, Cengage Learning.

Rhoades, Mark. 2015. SE4353 Risk Analysis and Management for Engineering Systems. Monterey, CA: Naval Postgraduate School.

Rupprecht, Johnathan. 2015. *Drones—Their Many Civilian Uses and The U.S. Laws Surrounding Them*. Version 2.03. United States: Wordpress.

SageTech. 2016. Accessed March 20, 2016. http://sagetechcorp.com/index.html.

Sailing Totem. 2014. Accessed February 27, 2016. http://www.sailingtotem.com/2014/06/safe-passagemaking-in-straits-of-malacca.html.

Savitz, Scott, Irv Blickstein, Peter Buryk, Robert Button, Paul DeLuca, James A. Dryden, Jason Mastbaum, et al. 2013. "U.S. Navy Employment Options for Unmanned Surface Vehicles (USVs). Research Report (Rand Corporation)." Santa Monica, CA: RAND. Accessed March 20, 2016. http://www.rand.org/pubs/research_reports/RR384.html.

Sin, M. L., and M. Cheang. 2015. "Survivability of Fearless Class Patrol Vessel against Terrorist Small Boat Threat." ME4571 Combat Survivability Engineering Project Report. Monterey, CA: Naval Postgraduate School.

Szondy, David. 2015. "GE Fires up Fully 3D-Printed Jet Engine." *Gizmag*. Accessed February 20, 2016. http://www.gizmag.com/ge-fires-up-all-3d-printed-jet-einge/37448/.

Thomas, Douglas S., and Stanley W. Gilbert. 2014. "Costs and Cost Effectiveness of Additive Manufacturing—A Literature Review and Discussion." NIST Special Publication 1176. Washington, DC: U.S. Department of Commerce.

United States Government Accountability Office. 2015. "3D Printing—Opportunities, Challenges, and Policy Implications of Additive Manufacturing." GAO-15-505SP. Accessed February 19, 2016. http://www.gao.gov/assets/680/670960.pdf

Vergakis, Brock. 2015. "Aircraft Carrier Harry S. Truman Prints Spare, Unique Parts at Sea with 3-D Printer." *The Virginian-Pilot*. Accessed February 19, 2016. http://pilotonline.com/news/military/local/aircraft-carrier-harry-s-truman-prints-spare-unique-parts-at/article_b46b30f0-2ad4-525f-8328-34d37034450c.html.

Weibel, Roland E., and R. John Hashman, Jr. 2005. "An Integrated Approach to Evaluating Risk Mitigation Measures for UAV Operational Concepts in the NAS." AIAA-2005-6957. *AIAA's 4th Infotech@Aerospace Conference*. 26–29 September 2005. Arlington, VA.

Weiss, Lee E. 1997. "Process Overview." *Japanese and World Technology Evaluation Centers*. Volume I. Baltimore: Loyola College in Maryland.

Wikimedia Commons. 2014. "File: MH370 Flight Path with English Labels.png." Accessed February 20, 2016. https://commons.wikimedia.org/wiki/File:MH370_flight_path_with_English_labels.png.

Williams, Richard. 2015. "UW2001 History of Mine Warfare" (lecture, Naval Postgraduate School, Monterey, CA, Winter 2016).

Wohlers, Terry., and Wohlers Associates. 2012 .Wohlers Report 2012: Additive Manufacturing and 3D Printing State of the Industry Annual: Annual Worldwide Progress Report. Fort Collins, Colorado: Wohlers Associates.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California